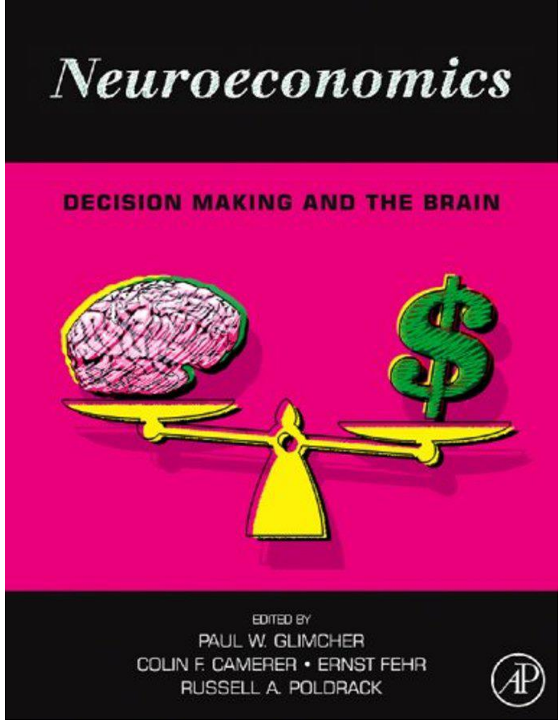
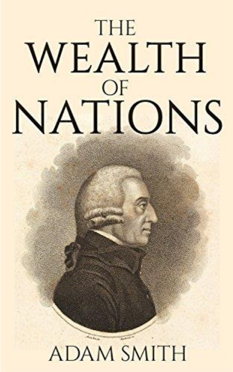
Neuroeconomics

How our brain decides



Conceptual map



History

Allais Paradox

Asian Disease

- **Lack of rationality**
- **We are social animals**

Study DECISION MAKING using psychology and neuroscience:

1) Options
2) Not random decisions
3) Goal-directed

METHODS of neuroeconomic and decision making

Electrical stimulation

Lesions

TMS

Single-cell recordings

EEG and MEG

fMRI

Inferior parietal lobe

Lateral intraparietal area

Low level decisions: Perceptual Decisions and Motion Decisions

Memory

Probability

Value/Utility

Emotions

High level decisions

Orbitofrontal cortex → options

Ventrolateral cortex → selfcontrol

DLPFC → planning and organization

aCC → learning consequences

Summary

- **A Sketch of the Relevant Circuitry**
- Nucleus Accumbens (Nacc)
- Orbitofrontal Cortex and Ventromedial Cortex: Evaluation of Options
- Dorsolateral Prefrontal Cortex and the Planning and Organization of Behavior
- Cingulate Cortex and Learning from the Consequences of Behavior
- Ventrolateral Prefrontal Cortex and Self-Control

A Sketch of the Relevant Circuitry

- Thinking, planning, and deciding draw on a suite of related mental activities that are loosely described under the rubric of **executive functions**
- Although this term alludes to managing corporate activities, it would be wrong to imagine that the brain actually works this way. It seems more apt to consider **executive functions as part of a control system** (a term borrowed from engineering) that adapts cognitive functions to the current environment and state of the organism
- Because several anatomical areas in the prefrontal cortex have been linked to these functions, it is tempting to conclude that each of these elements maps directly onto a specific brain region.

A Sketch of the Relevant Circuitry

The prefrontal cortex (PFC) is the portion of the frontal lobe anterior to the motor cortex in both humans and non-human primates, and it is especially prominent in humans.

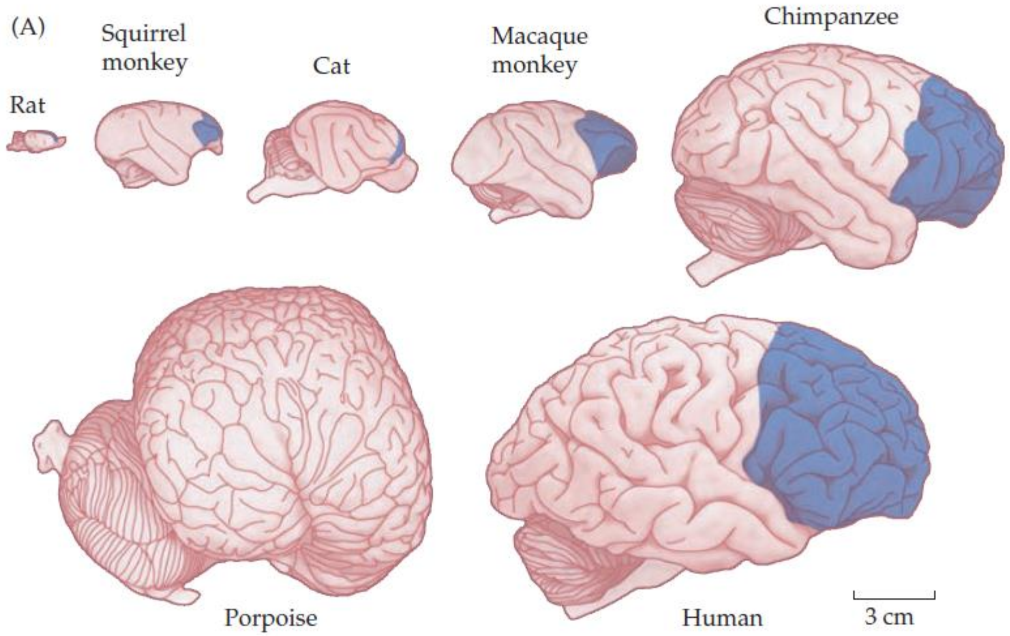
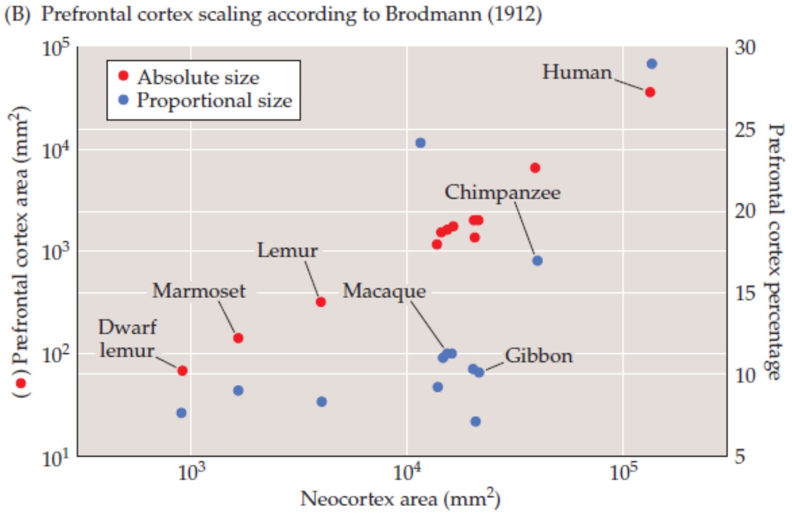
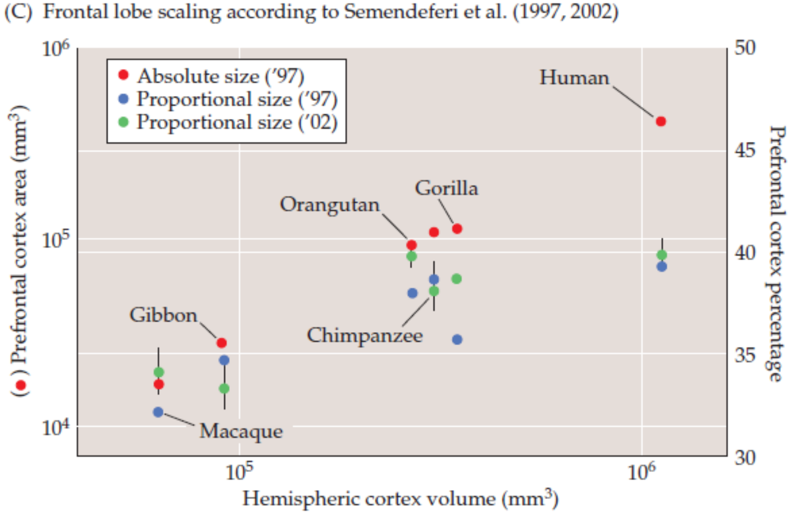


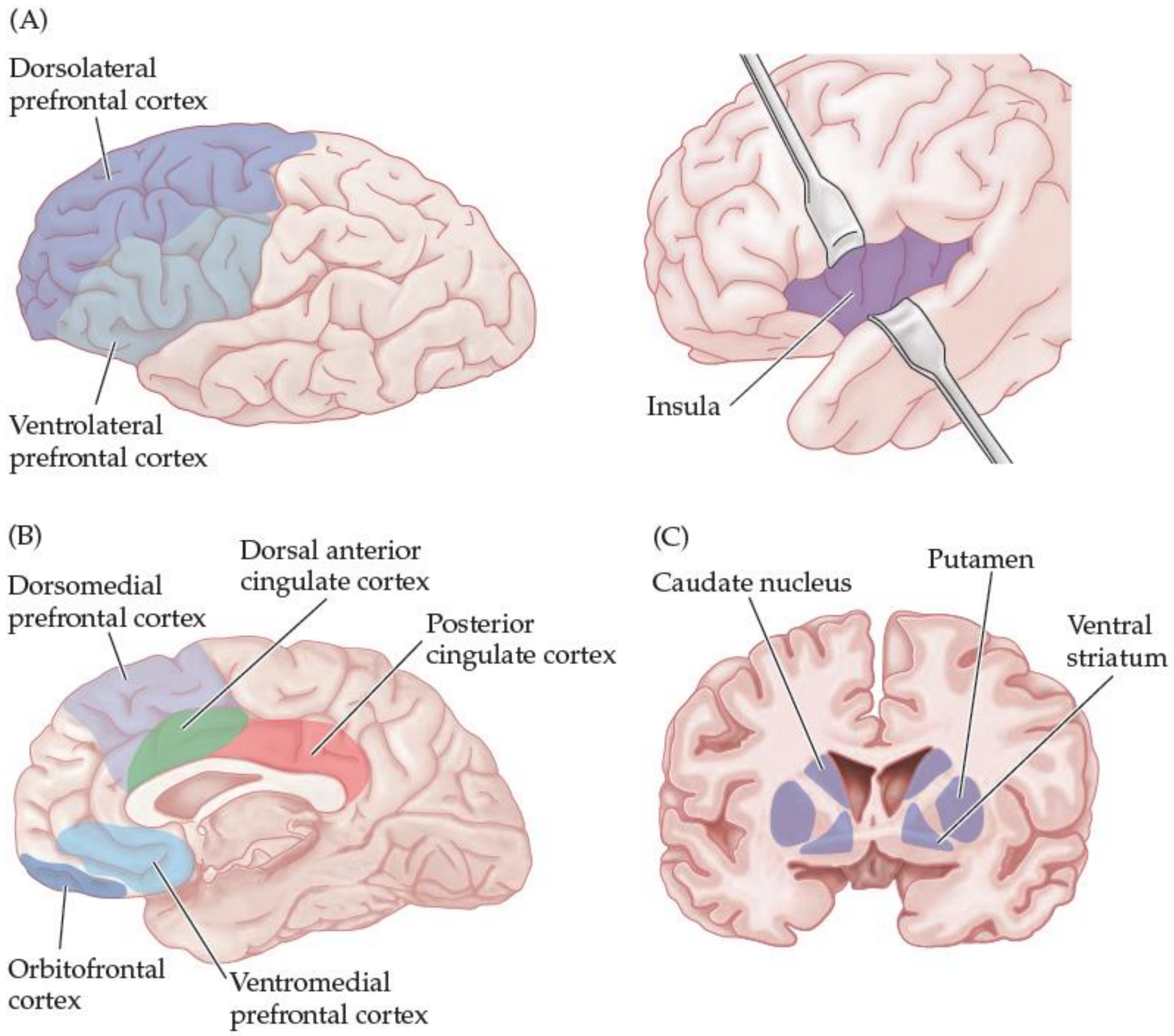
FIGURE 32.2 Size of the cerebral cortex and prefrontal cortex in mammals. (A) Among the seven species shown here, humans have the largest cerebral cortex but have a larger PFC (blue) relative to the other (non-primate) species, even controlling for brain size. The porpoise brain is provided for size comparison; its PFC is not indicated because the borders of it are not known. (B) Within the order of primates, the size of the PFC is roughly proportional to that of the rest of the neocortex. Brodmann's work in the early twentieth century had suggested that humans and other great apes have a disproportionately large PFC. (C) Later work has indicated that relative size of the PFC is roughly constant within the order of primates. (B after Brodmann, 1912; C after Semendeferi et al., 1997, 2002.)





A Sketch of the Relevant Circuitry

- No agreement on the histological boundaries defining subregions of PFC
- Not clearly defined electrophysiological properties of these reagions
- Impossible to identify the flow of information through the PFC: connections between different cortical regions are often reciprocal, and it is hard to differentiate which connections are feedback and which are feedforward.



A Sketch of the Relevant Circuitry

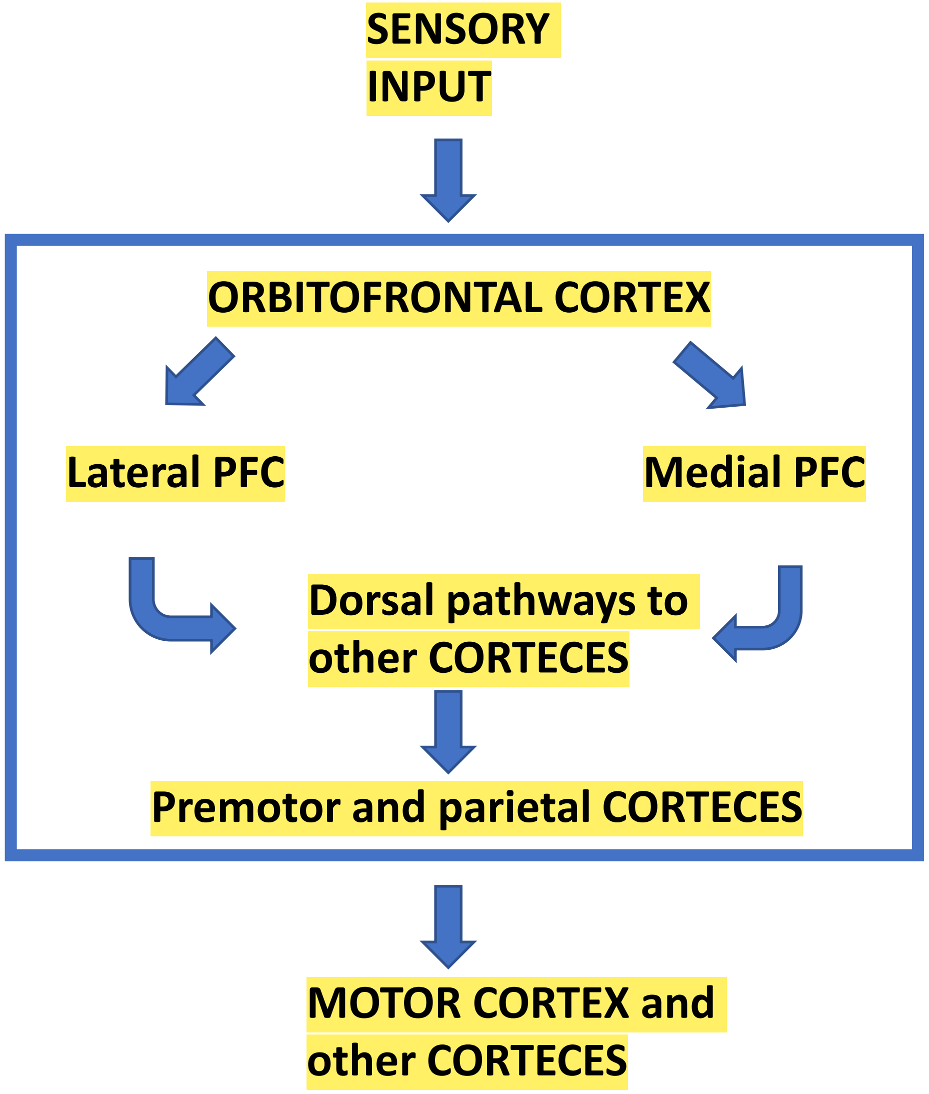
Despite this complexity, a **rough path** from input to output can be identified

1. Information about sensory stimuli is conveyed to the **orbitofrontal cortex**, where representations of the ***values*** of various options may be represented

2. Value signals the flow rostrally and laterally to the **lateral and medial PFC**, where information that influences decision making comes into play

3. Than, resulting signal flow **dorsally** to other PFC regions that use this information to plan possible responses

4. Finally, information propagate to **premotor** and **parietal** cortices and finally to the motor and other **cortical regions** that give rise to behavior (behavior is not limited to motor actions but also includes perception, attention, emotion, memory, and more)

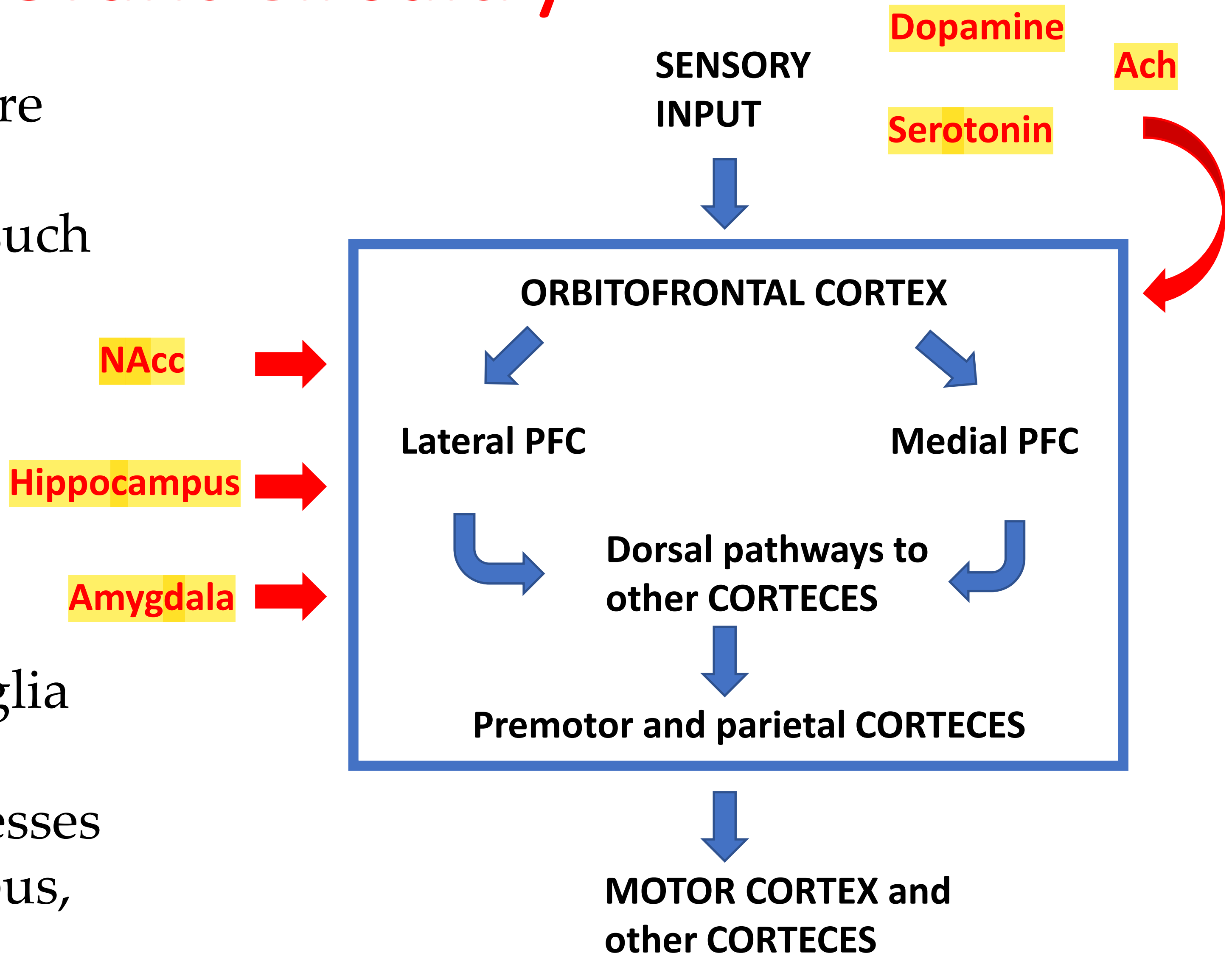


A Sketch of the Relevant Circuitry

These pathways and their targets are influenced
by neuromodulatory transmitters such as:

1. dopamine,
2. serotonin,
3. acetylcholine

4. by specialized cortico-basal ganglia loops;
5. by emotional and memory processes in the amygdala and hippocampus, respectively

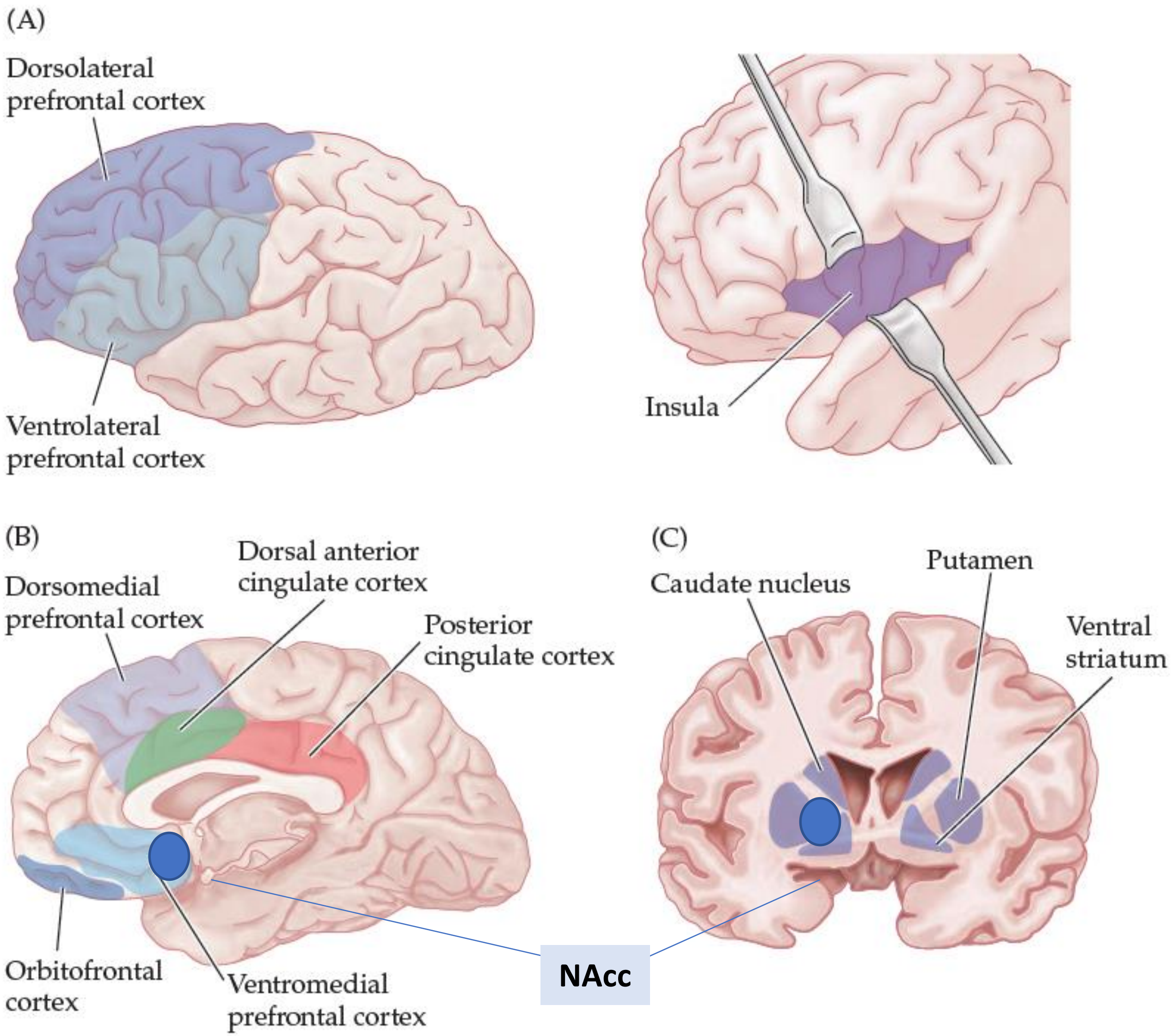


Summary

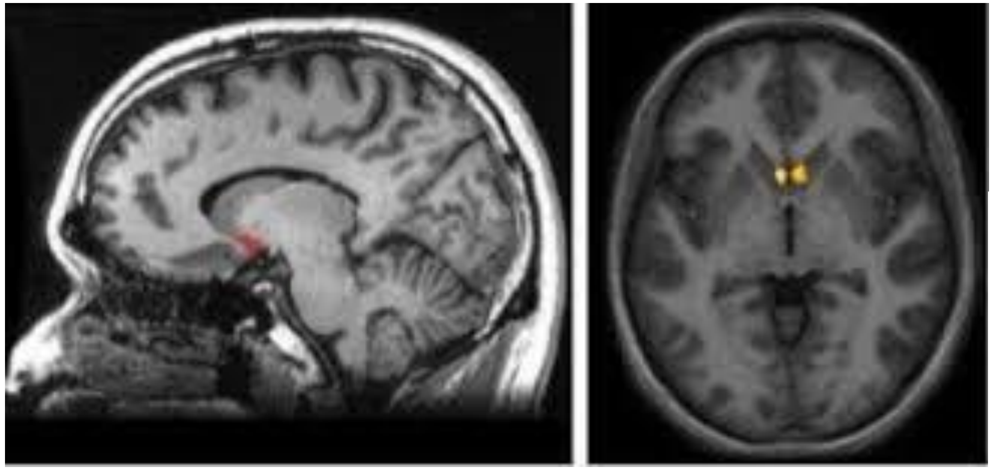
- A Sketch of the Relevant Circuitry
- **Nucleus Accumbens (Nacc)**
- Orbitofrontal Cortex and Ventromedial Cortex: Evaluation of Options
- Dorsolateral Prefrontal Cortex and the Planning and Organization of Behavior
- Cingulate Cortex and Learning from the Consequences of Behavior
- Ventrolateral Prefrontal Cortex and Self-Control

NAcc

- The nucleus accumbens, the pleasure area, is a key area for the evaluation process.
- This area actually encodes our expected values during the decision making



Nucleus accumbens (NAcc) – ventral striatum



Nucleus accumbens

NAcc gets information from:

1) Hippocampus (region related to memory)
2) Prefrontal cortex (region involved into the higher order decision processes)
3) Amigdala (region related to motivation and cost of our decisions)
4) Ventral tegmental area (reward prediction and Salience)

Neuroscientist. 2007 April ; 13(2): 148–159. doi:10.1177/1073858406295854.

The Nucleus Accumbens and Pavlovian Reward Learning

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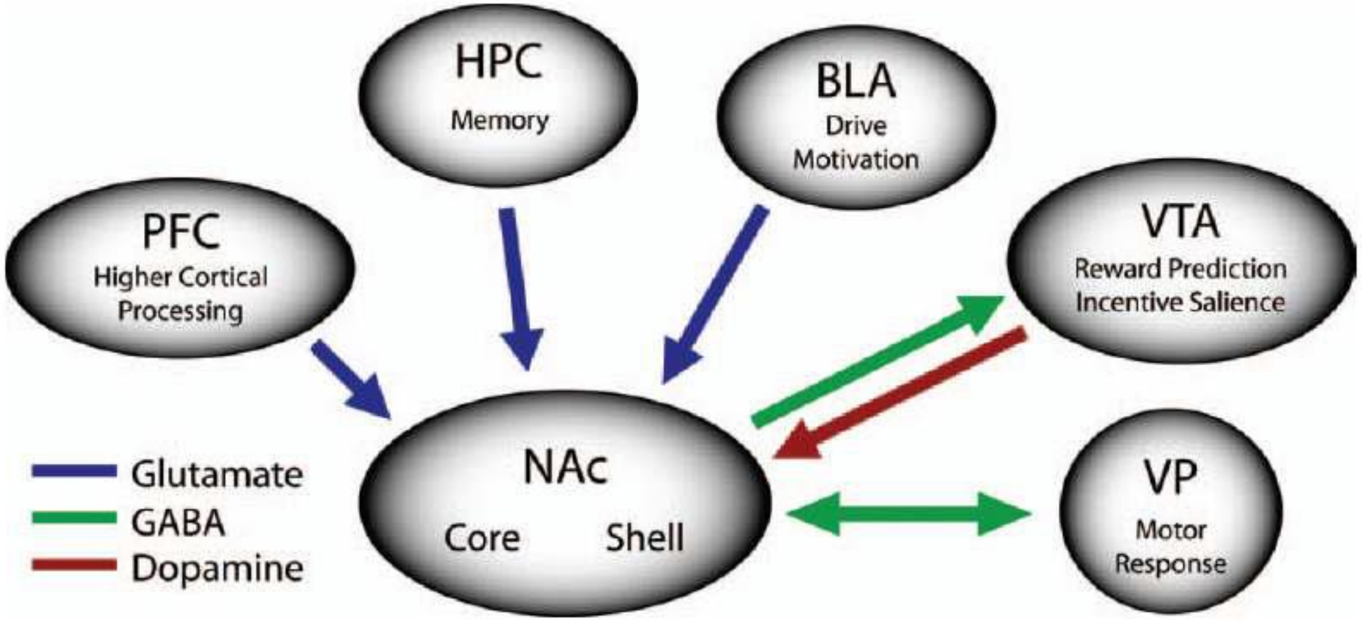


Fig. 1. General overview of key nucleus accumbens (NAc) afferent and efferent projections. See text for more information on the anatomic organization of the NAc. Note that placement of arrows does not necessarily indicate degree or precise location of projection. PFC, prefrontal cortex; HPC, hippocampus; BLA, basolateral amygdala; VTA, ventral tegmental area; VP, ventral pallidum; NAc, nucleus accumbens.

Nucleus accumbens (NAcc) – ventral striatum

- The authors recorded the impulse activity of single neurons in monkeys that were trained in two behavioral tasks employing, respectively, self-initiated and externally timed movements
- When the monkey touches reward spikes produced by the NA appear
- When the monkey touches an object, there is no reward and no activation of the NAcc

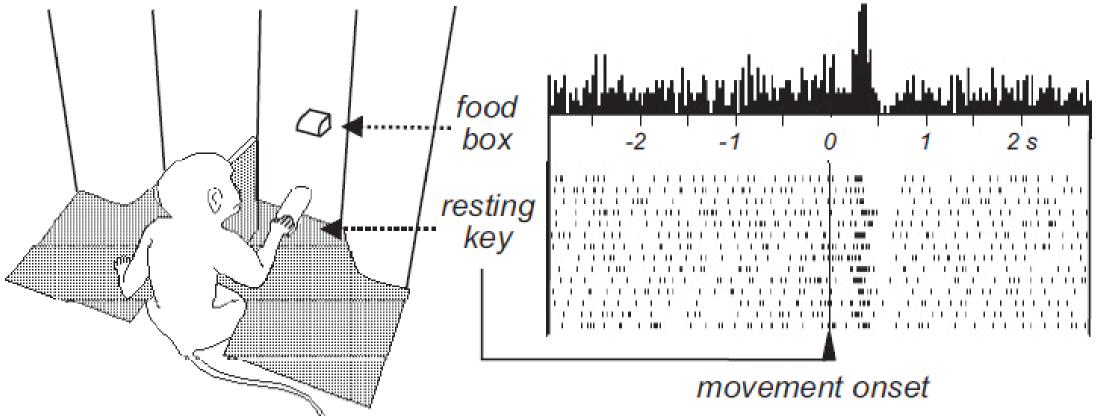
Brain Research

Research Note

Neuronal activity preceding self-initiated or externally timed arm movements in area 6 of monkey cortex

R. Romo and W. Schultz

Institut de Physiologie, Université de Fribourg, CH–1700 Fribourg, Switzerland



each line represents one trial

NAcc codes for reward and prediction of reward

- Animals learn not only about stimuli that predict reward but also about those that signal the omission of an expected reward
- The authors trained 2 monkeys in a discrimination task in which they had to recognize:

  A: a visual stimulus that predicted reward (conditioned excitor)

  AX: a stimulus that predicted the omission of reward (conditioned inhibitor)

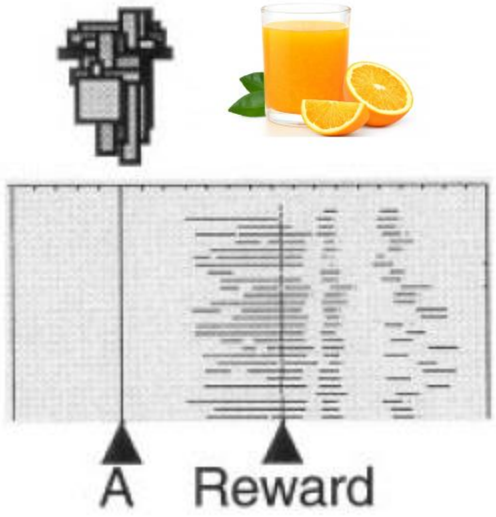
10402 • The Journal of Neuroscience, November 12, 2003 • 23(32):10402–10410

Behavioral/Systems/Cognitive

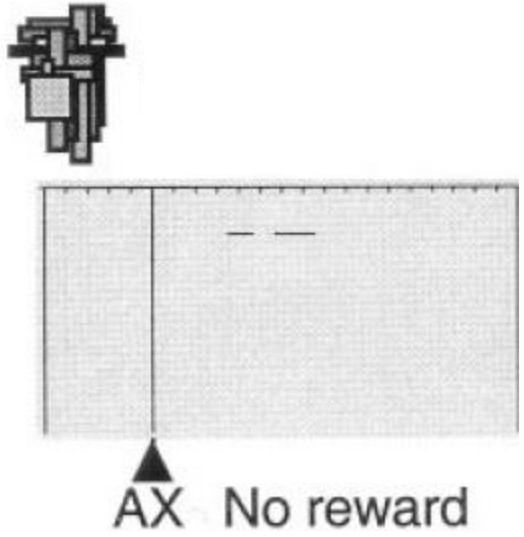
Coding of Predicted Reward Omission by Dopamine Neurons in a Conditioned Inhibition Paradigm

Philippe N. Tobler,[1] Anthony Dickinson,[2] and Wolfram Schultz[1]
[1]Department of Anatomy, University of Cambridge, Cambridge CB2 3DY, United Kingdom, and Institute of Physiology, University of Fribourg, 1700 Fribourg, Switzerland, and [2]Department of Experimental Psychology, University of Cambridge, Cambridge CB2 3EB, United Kingdom

Conditioned stimulus



Conditioned stimulus



NAc codes for reward and prediction of reward

A: a visual stimulus that predicted reward (conditioned excitor)

AX: a stimulus that predicted the omission of reward (conditioned inhibitor)

When animal get reward → bursts of activity **and** no depression

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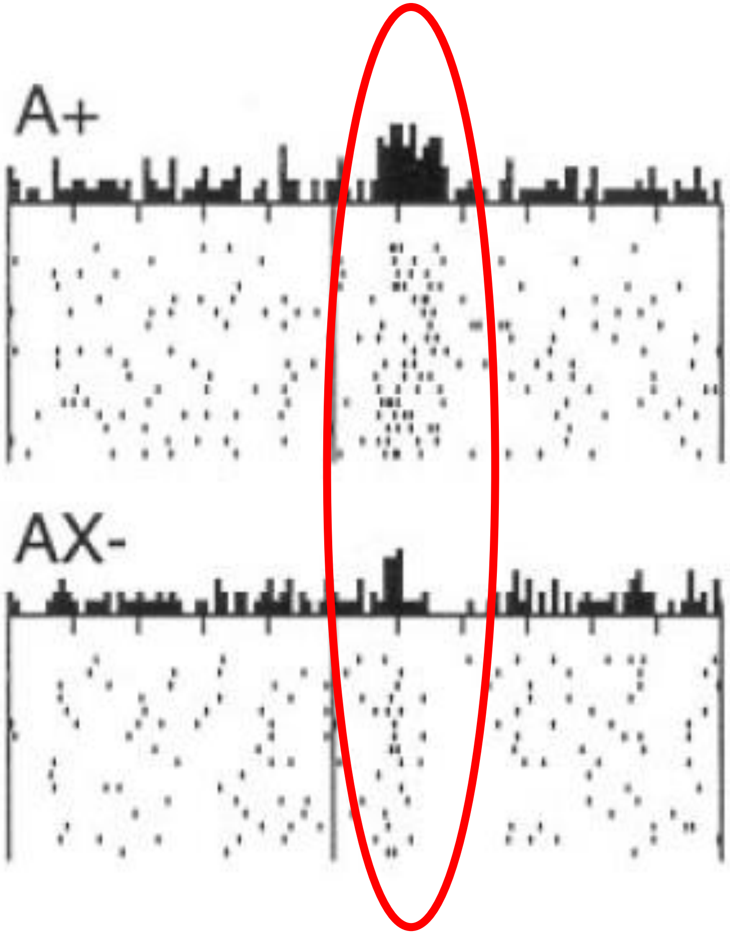

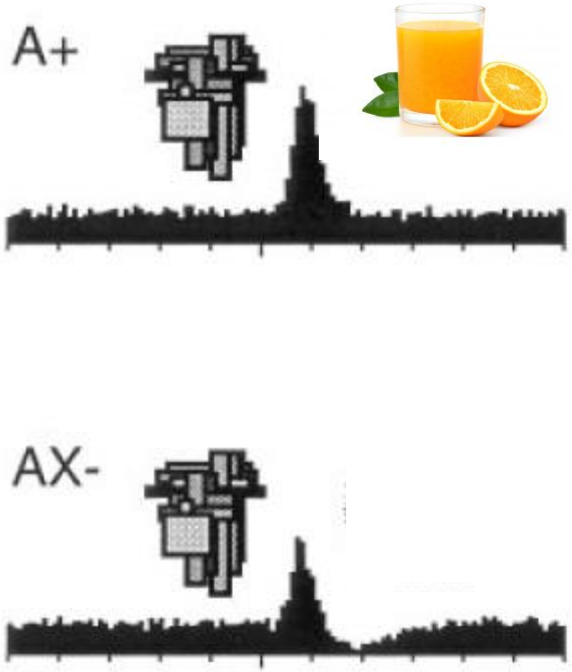

NAcc codes for expected reward

Annu. Rev. Psychol. 2006. 57:87–115
doi: 10.1146/annurev.psych.56.091103.070229

First published online as a Review in Advance on September 16, 2005

BEHAVIORAL THEORIES AND THE NEUROPHYSIOLOGY OF REWARD

Wolfram Schultz
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During the conditioning process, this neuron **stops to react to reward** → it reacts to the prediction of reward →**to the expected values**

DOPAMINE NEURONS ACTUALLY CODE TO EXPECTED REWARDS

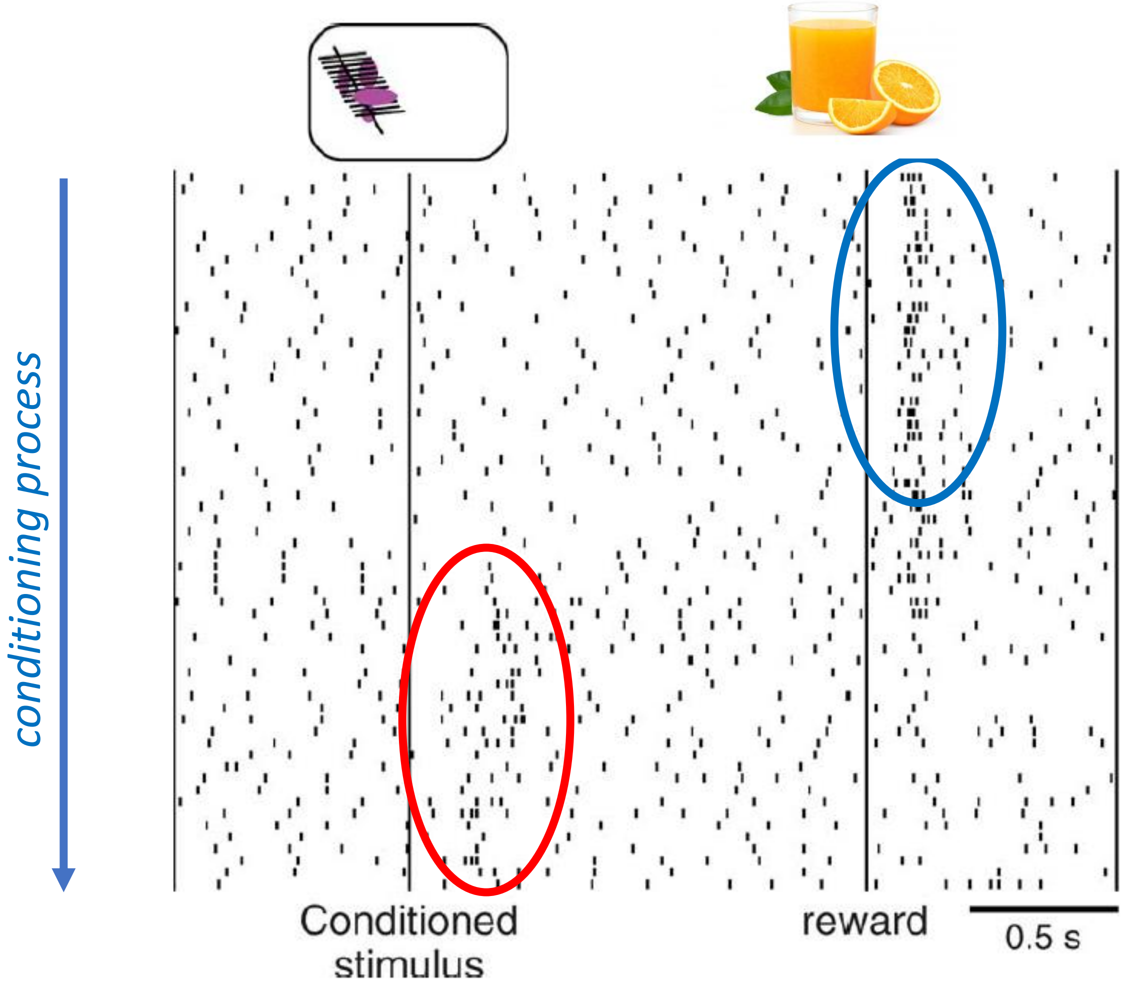
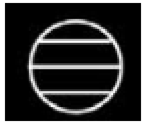


Figure 2 Testing the contiguity requirement for associative learning: acquisition of neural response in a single dopamine neuron during a full learning episode. Each line of dots represents a trial, each dot represents the time of the discharge of the dopamine neuron, the vertical lines indicate the time of the stimulus and juice reward, and the picture above the raster shows the visual conditioned stimulus presented to the monkey on a computer screen. Chronology of trials is from top to bottom. The top trial shows the activity of the neuron while the animal saw the stimulus for the first time in its life, whereas it had previous experience with the liquid reward. Data from Waelti (2000).

NAcc codes for values

- In this study, authors used a parametric monetary incentive delay (MID) task.
- N = 12 healthy volunteers participated in fMRI scans while playing the MID task.
- Subjects see a cue



More lines more money

- Then, after a delay, a white square appears.
- If subjects press the bottom in time → collects the reward

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NeuroImage
NeuroImage 18 (2003) 263–272
www.elsevier.com/locate/ynimg

A region of mesial prefrontal cortex tracks monetarily rewarding outcomes: characterization with rapid event-related fMRI

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Received 18 July 2002; accepted 14 October 2002

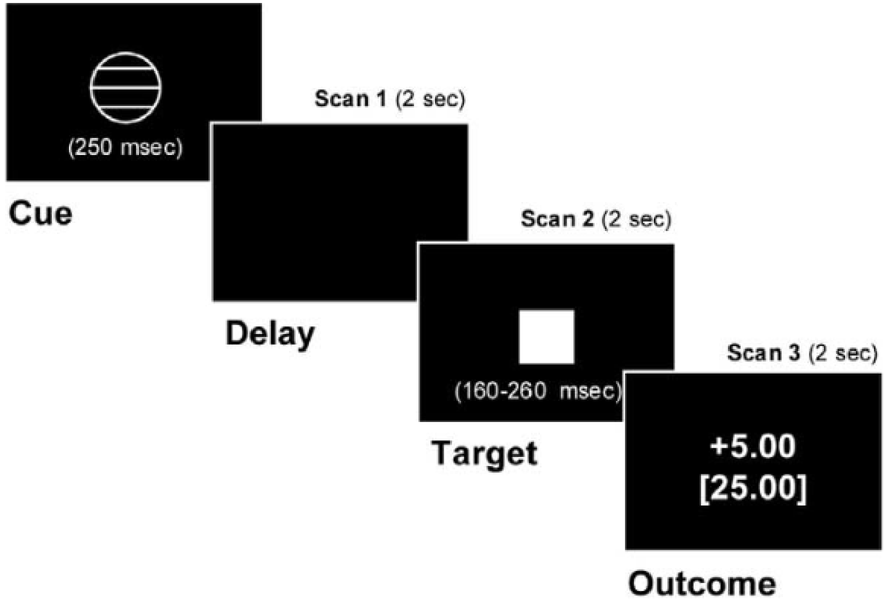


Fig. 1. Task structure for a representative trial.

NAcc codes for values

- Activity of the nucleus accumbens is proportional to the anticipated gain
- It is less active when person expects to get $1, and is even less active when person expects to get $0

- **Activity of the ventral striatum is proportional to the anticipated gain**
- Activity of the ventral striatum is higher during the anticipation phase (compared to the outcome phase)

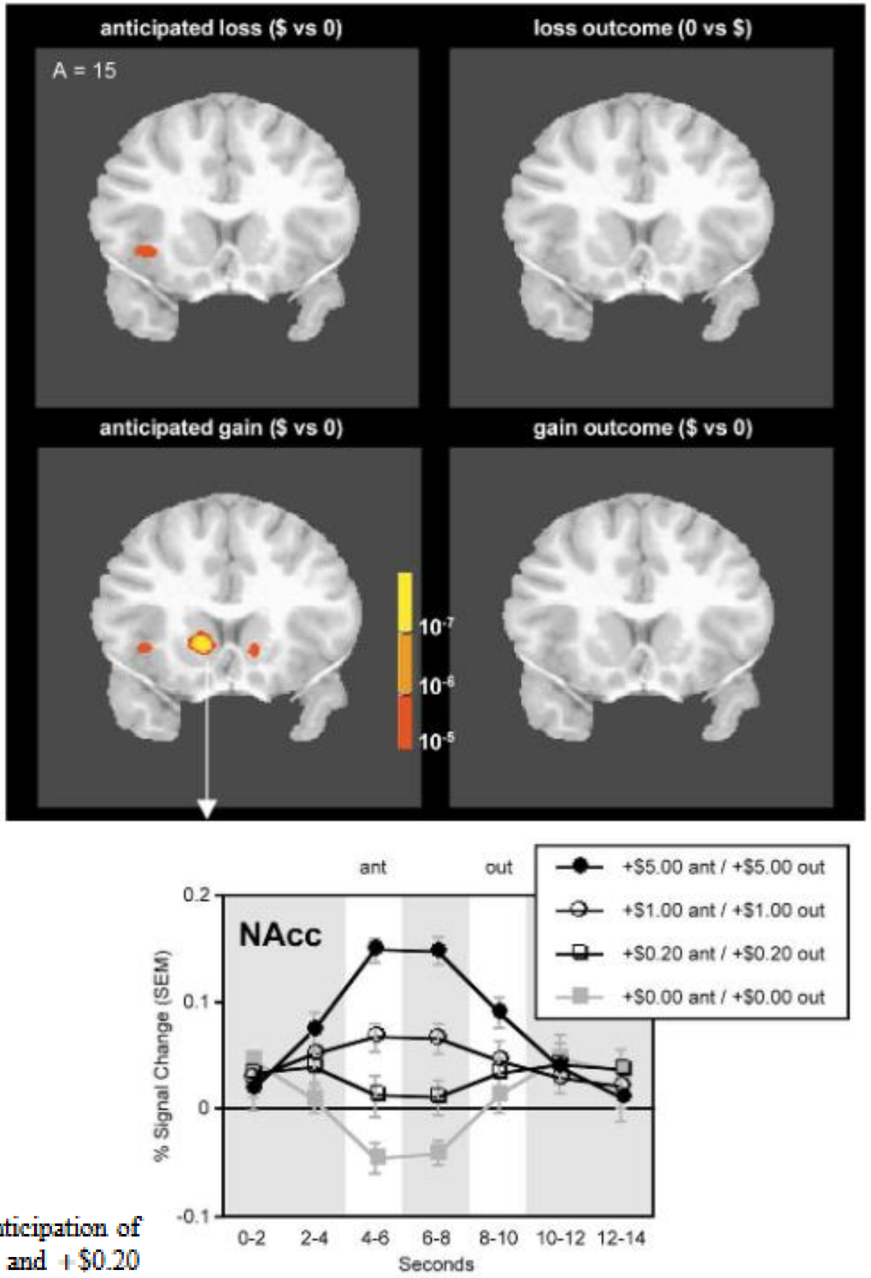
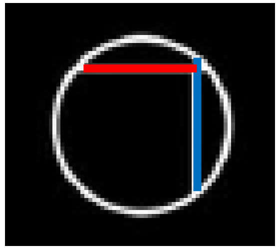


Fig. 3. Group maps (n = 12) in the coronal plane contrasting: (1) anticipation of −$5.00, −$1.00, and −$0.20 vs −0.00 (upper left); (2) anticipation of +$5.00, +$1.00, and +$0.20 vs +0.00 (lower left); (3) −0.00 vs −$5.00, −$1.00, and −$0.20 outcome (upper right); (4) +$5.00, +$1.00, and +$0.20 vs +0.00 outcome (lower right). The bottom figure depicts averaged time courses from a right NAcc volume of interest. Group maps are superimposed onto the spatially normalized structural scan of a representative volunteer, which has been sectioned at Anterior = 15 mm.

Expected utility

- AIM: **Anticipated reward** magnitude and **probability** comprise dual components of expected value (EV), a cornerstone of economic and psychological theory. However, the neural mechanisms that compute EV have not been characterized.
- Using event-related functional magnetic resonance imaging, authors examined **neural activation** as subjects anticipated monetary gains and losses that varied in magnitude and probability.
- N = 14



magnitude

probability

EV

4806 • The Journal of Neuroscience, May 11, 2005 • 25(19):4806–4812

Behavioral/Systems/Cognitive

Distributed Neural Representation of Expected Value

Brian Knutson,[1] Jonathan Taylor,[2] Matthew Kaufman,[1] Richard Peterson,[1] and Gary Glover[3]
Departments of [1]Psychology, [2]Statistics, and [3]Radiology, Stanford University, Stanford, California 94305

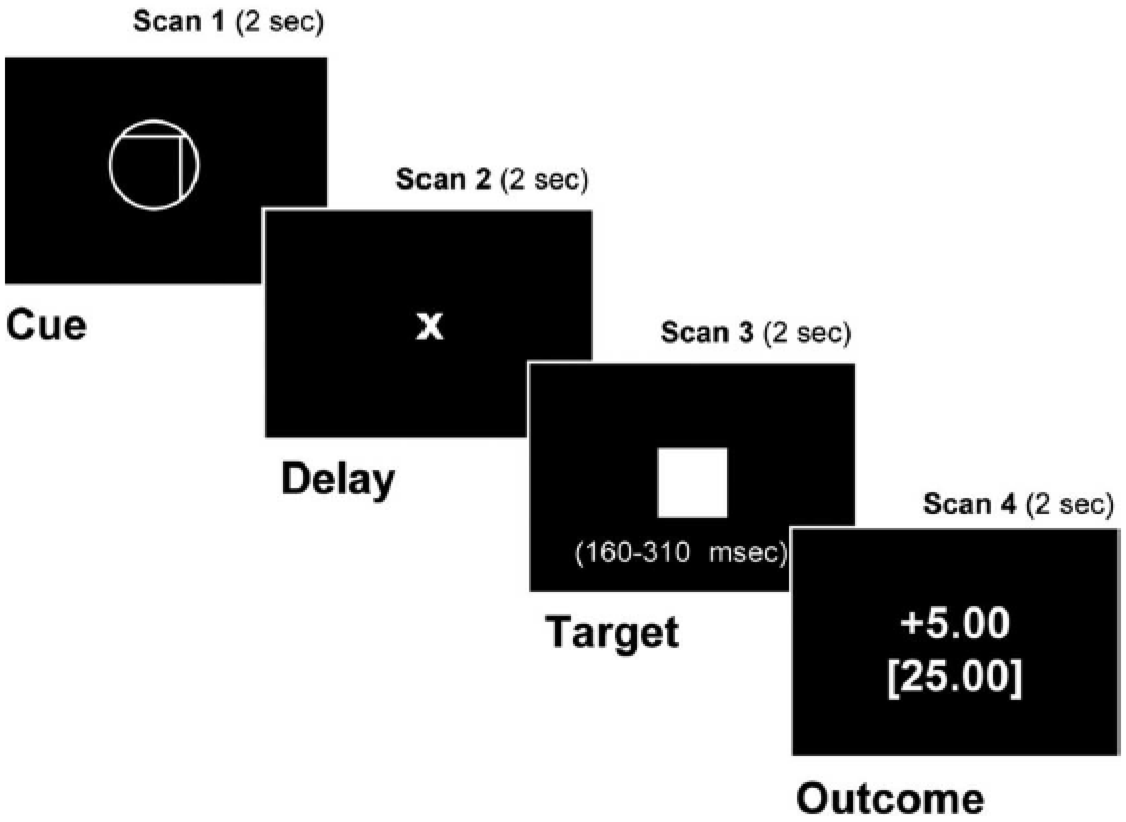


Figure 1. Probabilistic monetary-incentive delay-task trial structure.

Expected utility

- Subject has to press the button when the white square is presented

- In this case: high probability and high reward → 5 dollars

4806 • The Journal of Neuroscience, May 11, 2005 • 25(19):4806–4812

Behavioral/Systems/Cognitive

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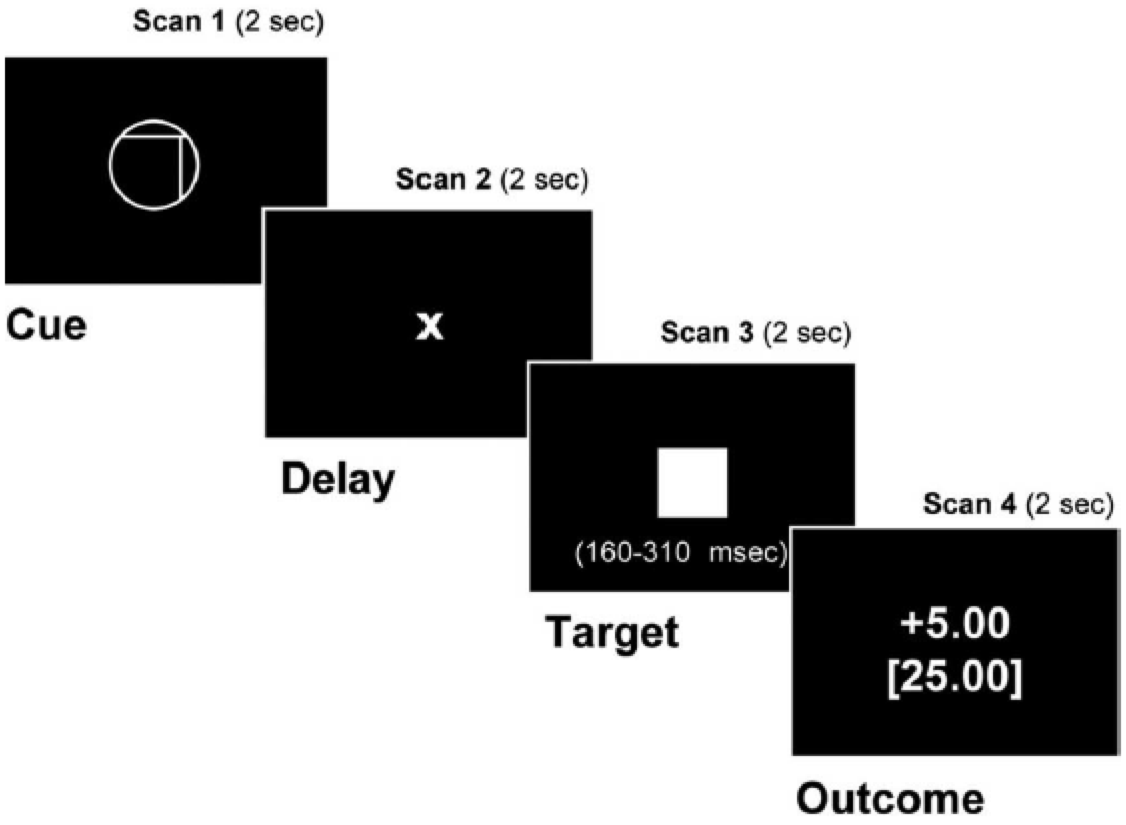


Figure 1. Probabilistic monetary-incentive delay-task trial structure.

Expected utility

- NAcc codes for expected values →nucleus accumbens (NAcc) activated proportional to anticipated gain magnitude

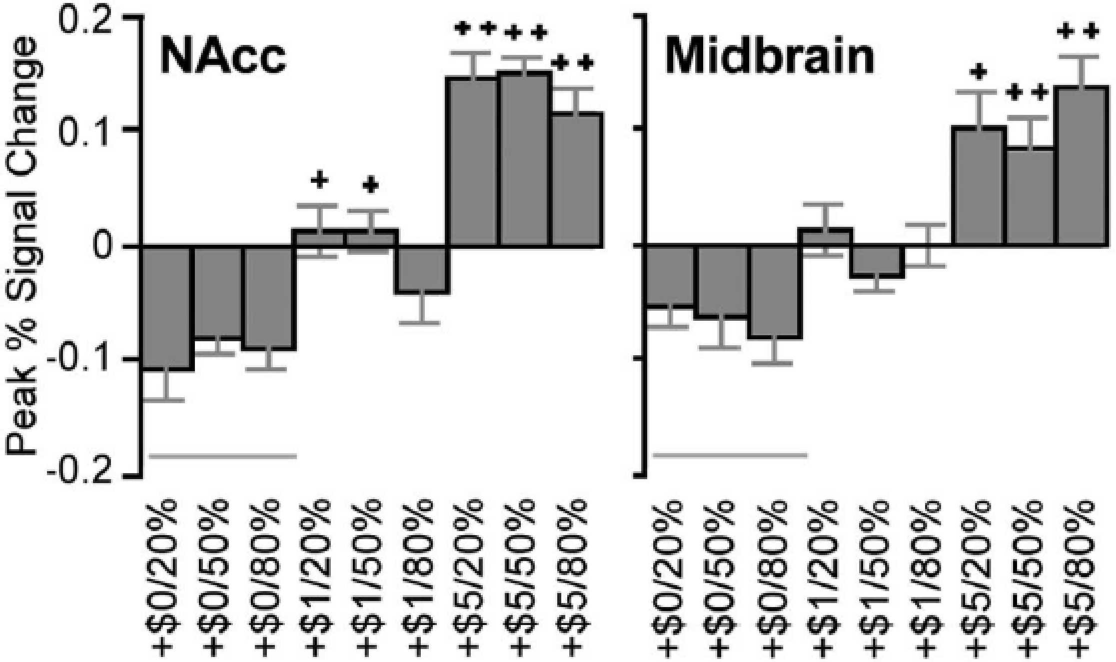


Figure 4. Peak percentage signal change by gain trial type for right VOIs. Bars represent means ± SEM ($n = 14$). Trial alignment (left to right) reflects expected value (low to high). Symbols indicate significant difference from the low (+, >\$0.00) and middle (++, >\$1.00 and >\$0.00) magnitude incentive conditions, matched for valence and probability (within-subject pairwise comparisons; $p < 0.005$, corrected for 9 comparisons). ACing, Anterior cingulate. Error bars represent SEM.

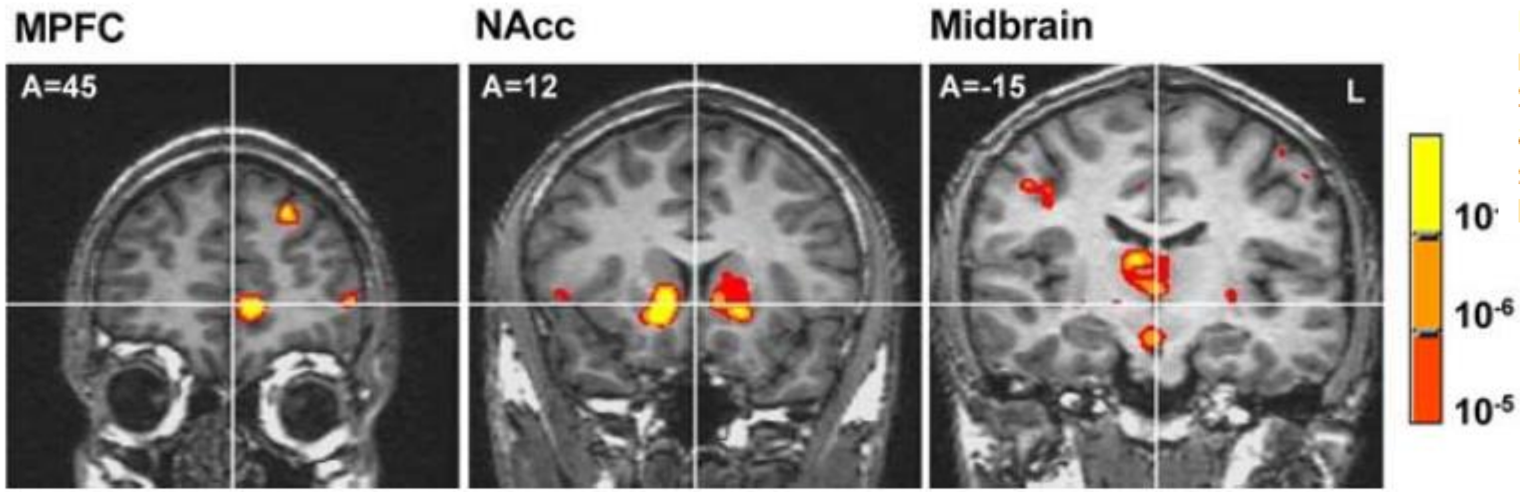


Figure 2. Group maps of regions whose activation correlates with the linear model of expected value. Warm colors signify activation, whereas cool colors signify deactivation (threshold, $p < 10^{-5}$). A, Anterior; L, left.

Expected utility

- The cortical mesial prefrontal cortex (MPFC) is additionally activated according to anticipated gain probability

- MPFC activation correlated with probability estimates

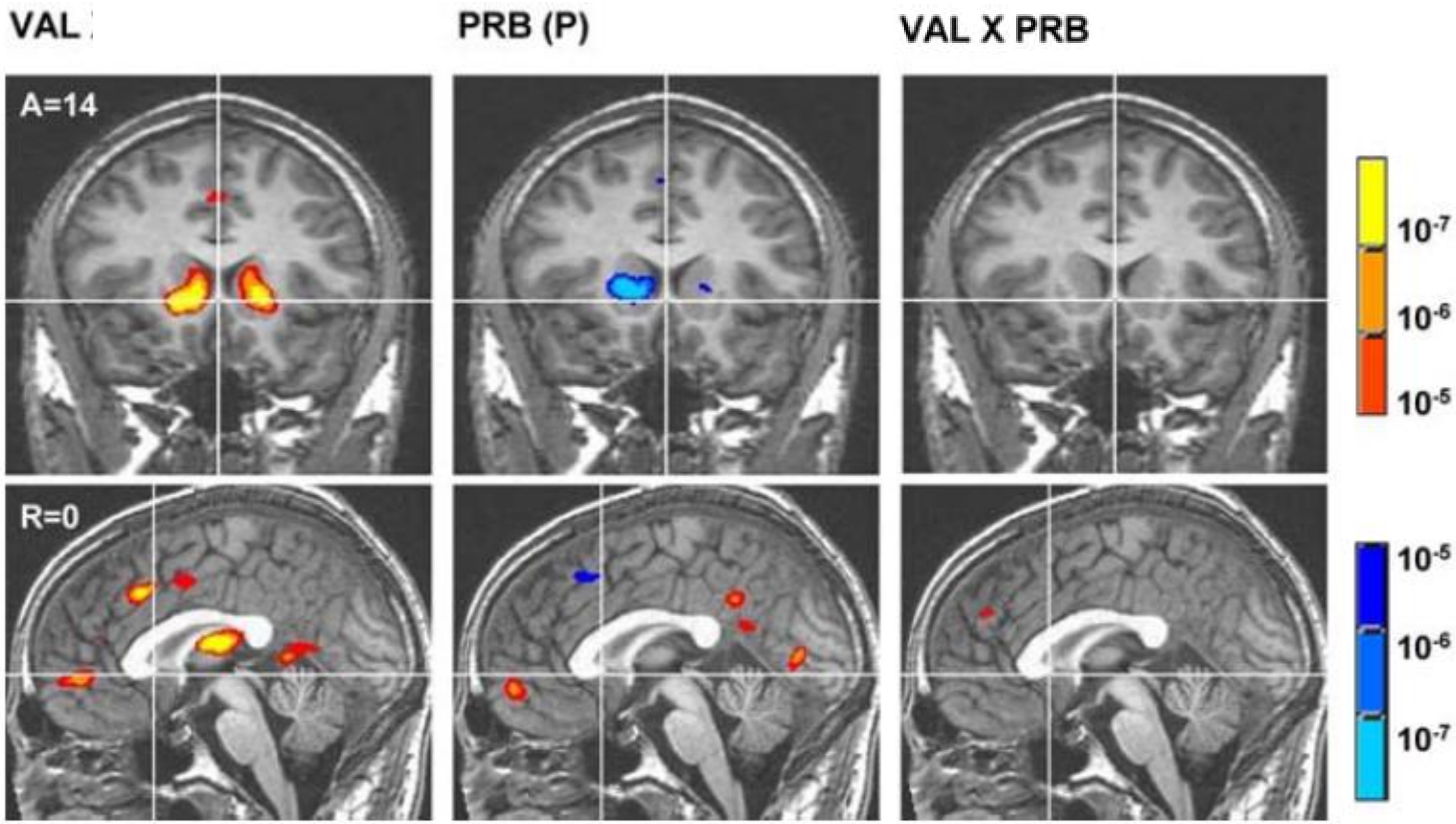


Figure 3. Group maps of contrasts related to distinct terms of expected value. Maps illustrate the interaction of VAL by MAG (V), the main effect of PRB (P), and the interaction of VAL by MAG by PRB (EV). Warm colors signify activation, whereas cool colors signify deactivation (threshold, $p < 10^{-5}$). A, Anterior; R, right.

These findings suggest that mesolimbic brain regions support the **computation of EU in an ascending and distributed manner**: whereas subcortical regions represent an affective component, cortical regions also represent a probabilistic component, and, furthermore, may act as integrators

Expected utility

Cellular/Molecular

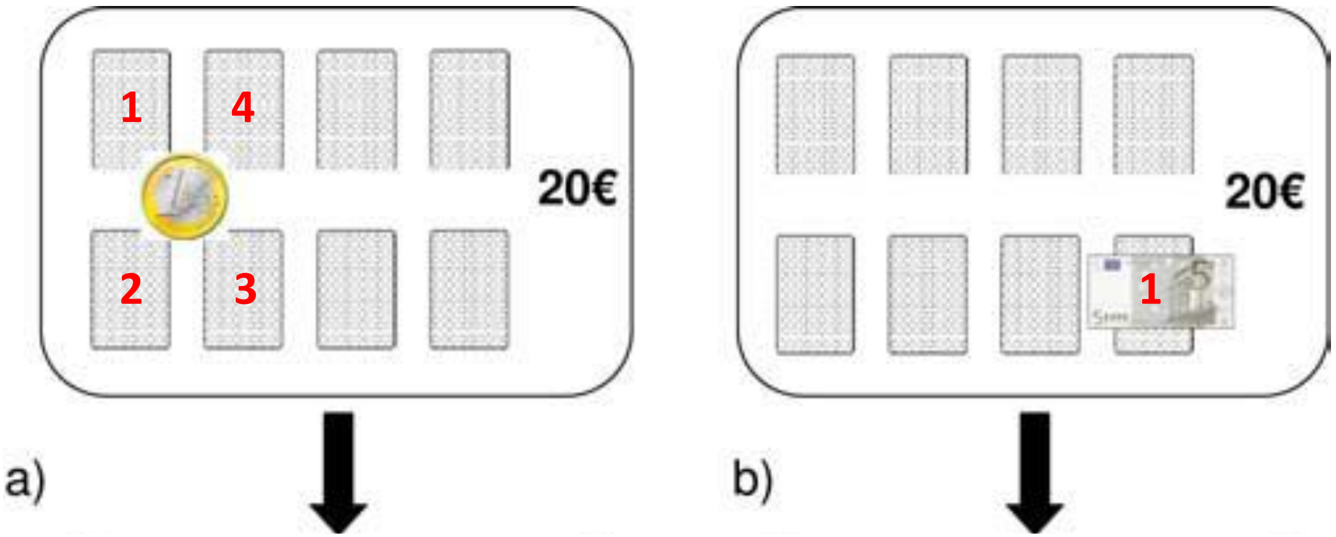
Dissociable Systems for Gain- and Loss-Related Value Predictions and Errors of Prediction in the Human Brain

Juliana Yacubian,[1*] Jan Gläscher,[1*] Katrin Schroeder,[2] Tobias Sommer,[1] Dieter F. Braus,[2] and Christian Büchel[1]
Departments of [1]Systems Neuroscience and [2]Psychiatry, NeuroImage Nord, University Medical Center Hamburg-Eppendorf, D-20246 Hamburg, Germany

- fMRI and a guessing task in two cohorts of 22 and 24 participants
- Participants have to predict the location of a red card

a) Participants can turn 4 cards →they can correctly predict the location of the red card (high probability)

b) Participants can turn 1 card →they have to guess the location (low probability)



Expected utility

- We can also manipulate the gain of the game

a) 21 euros

b) 15 euros

Cellular/Molecular

Dissociable Systems for Gain- and Loss-Related Value Predictions and Errors of Prediction in the Human Brain

Juliana Yacubian,[1*] Jan Gläscher,[1*] Katrin Schroeder,[2] Tobias Sommer,[1] Dieter F. Braus,[2] and Christian Büchel[1]
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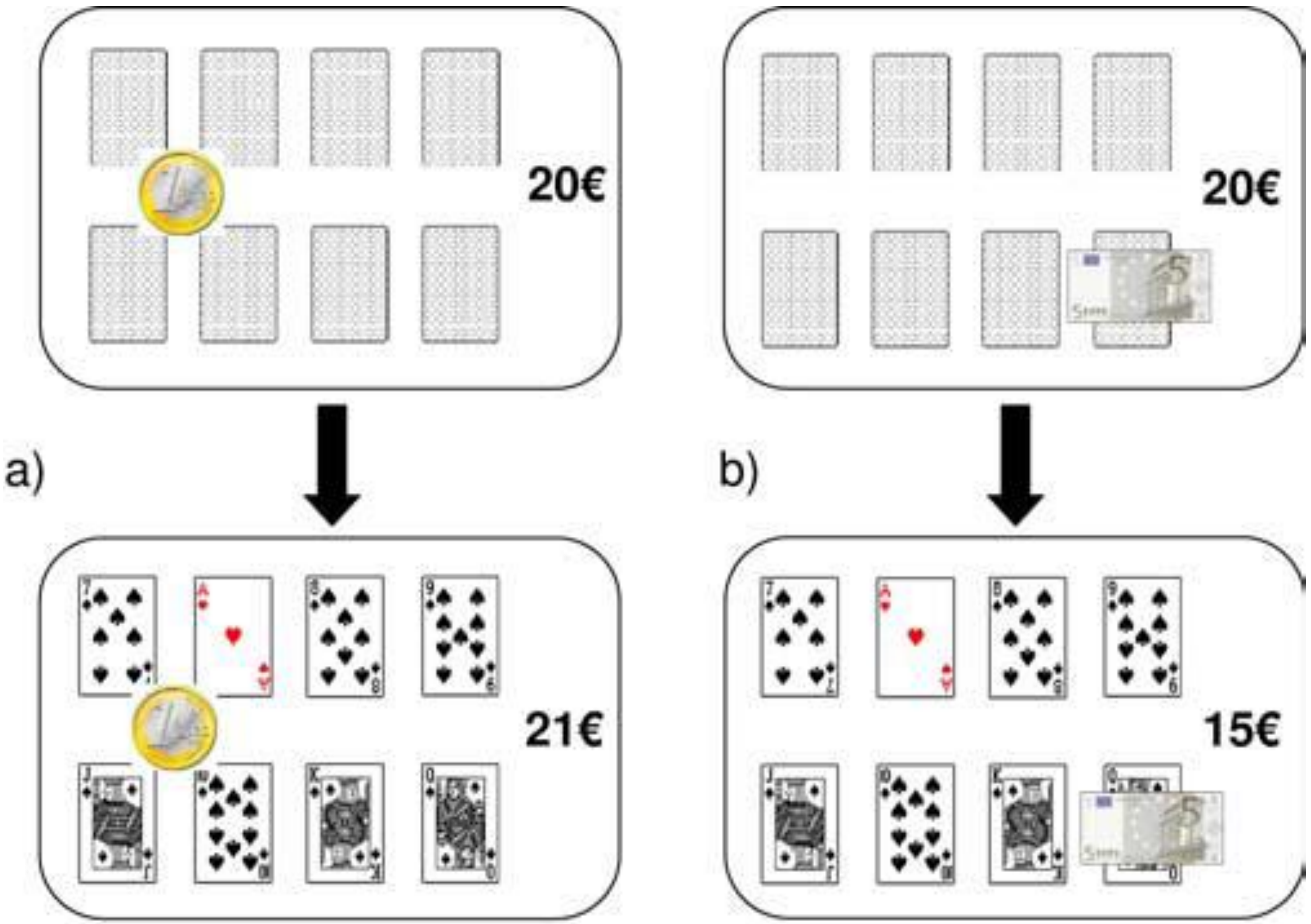
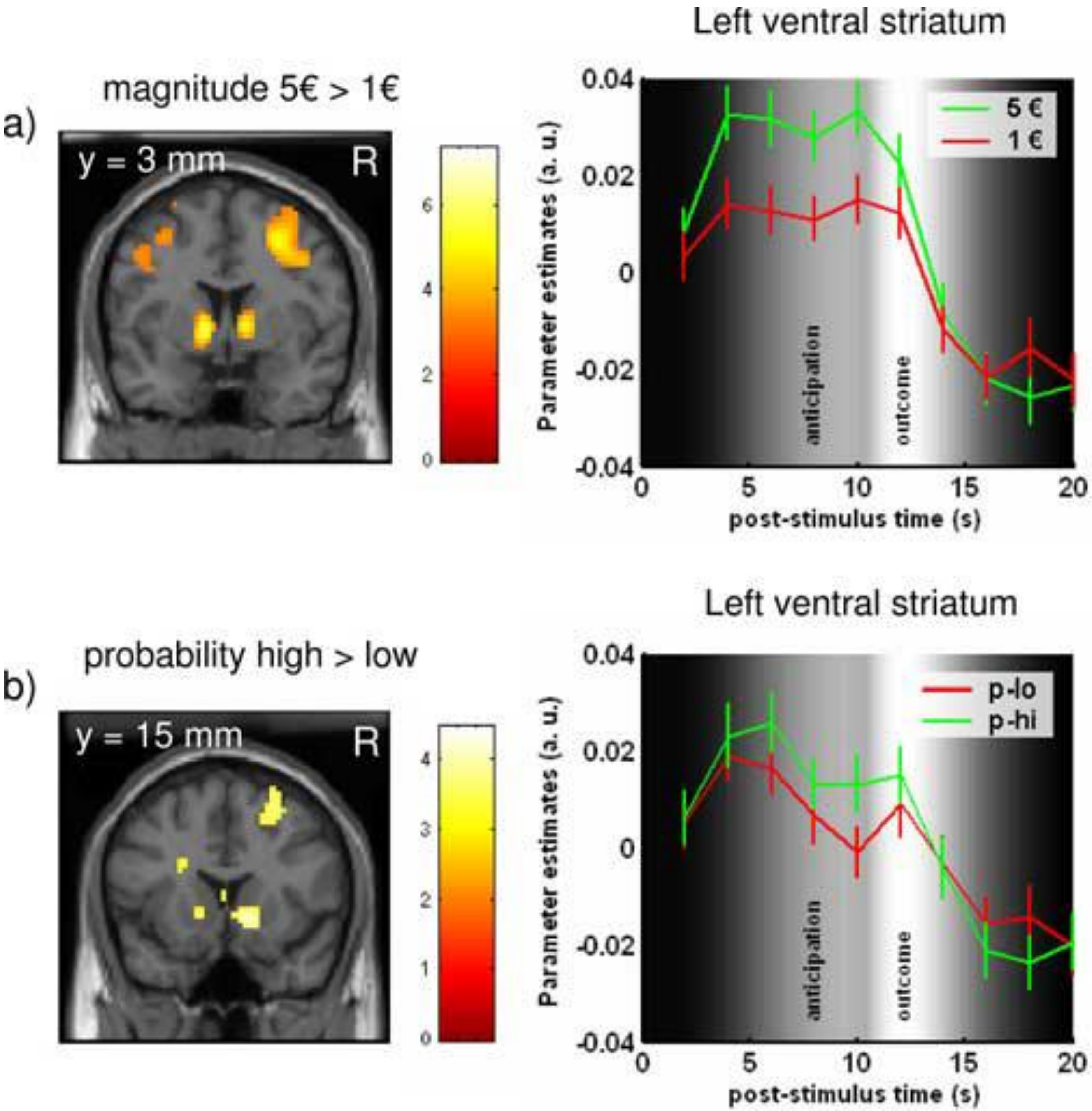


Expected utility

- Activity of nucleus accumbens is proportional to the expected magnitude of the reward.
- NAcc is strongly activated when subject is expecting to get higher reward.
- NAcc reacts to the probability of the outcome (high activity when participants expected reward with higher probability).



Role of NAcc: it calculates expected utility

- According to the neuroeconomics model: subjective value (utility) is the averaged firing rate of neurons in specific brain regions. These neurons code behavioral preferences.

- Specific brain regions → NAcc

- NAcc activity codes valence and it is proportional to anticipated gain magnitude.
- Nacc has neurons that are sensitive to probability

Nacc in the “real” world

- The above mentioned studies considered “experimental conditions”

- How about the role of Nacc in more practical conditions. Does it reproduce our decision making processes when we have to buy something?

Role of NAcc

- Microeconomic theory maintains that purchases are driven by a combination of consumer preference and price. Using event-related fMRI, we investigated how people weigh these factors to make purchasing decisions.
- N = 26
- Subjects were paid $20.00 per hour for participating and also received $20.00 in cash to spend on products during each of the two sessions.
- To ensure subjects' engagement in the SHOP task, one trial was randomly selected after each scanning session to count ''for real''.' If subjects had chosen to purchase the product presented during the randomly selected trial, they paid the price that they had seen in the scanner from their $20.00 endowment and were shipped the product within two weeks. If not, subjects kept their $20.00 endowment.

Neuron
Article

Neural Predictors of Purchases

Brian Knutson,[1,*] Scott Rick,[2] G. Elliott Wimmer,[1] Drazen Prelec,[3] and George Loewenstein[2]
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DOI 10.1016/j.neuron.2006.11.010

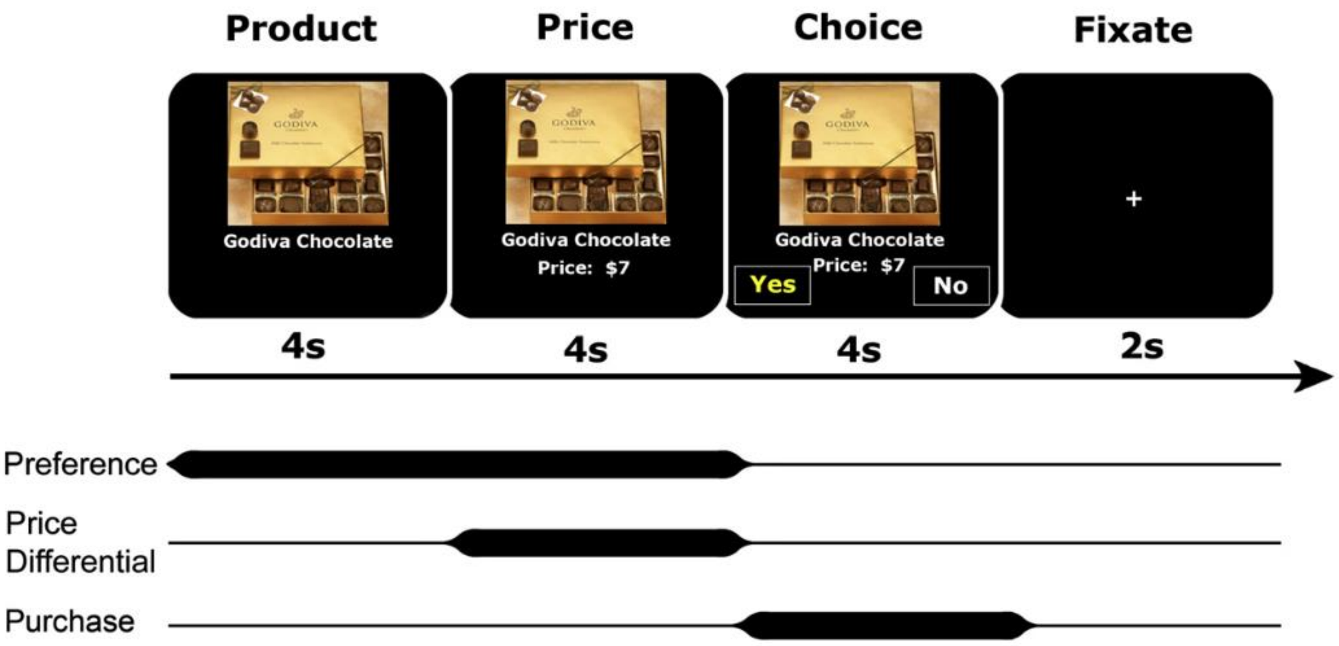

Figure 1. SHOP Task Trial Structure and Regressors
For task structure, subjects saw a labeled product (product period; 4 s), saw the product's price (price period; 4 s), and then chose either to purchase the product or not (by selecting either "yes" or "no" presented randomly on the right or left side of the screen; choice period; 4 s), before fixating on a crosshair (2 s) prior to the onset of the next trial. In regression models, preference was correlated with brain activation during the product and price periods, price differential was correlated with brain activation during the price period, and purchasing was correlated with brain activation during the choice period.

Role of NAcc

- Question:

Can we predict participant's decision to buy or not the product ("read" his/her mind) during the preference phase"?

- Answer: Yes.

The activity of the NAcc is higher when the participant buys the product

Neuron
Article

Neural Predictors of Purchases

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DOI 10.1016/j.neuron.2006.11.010

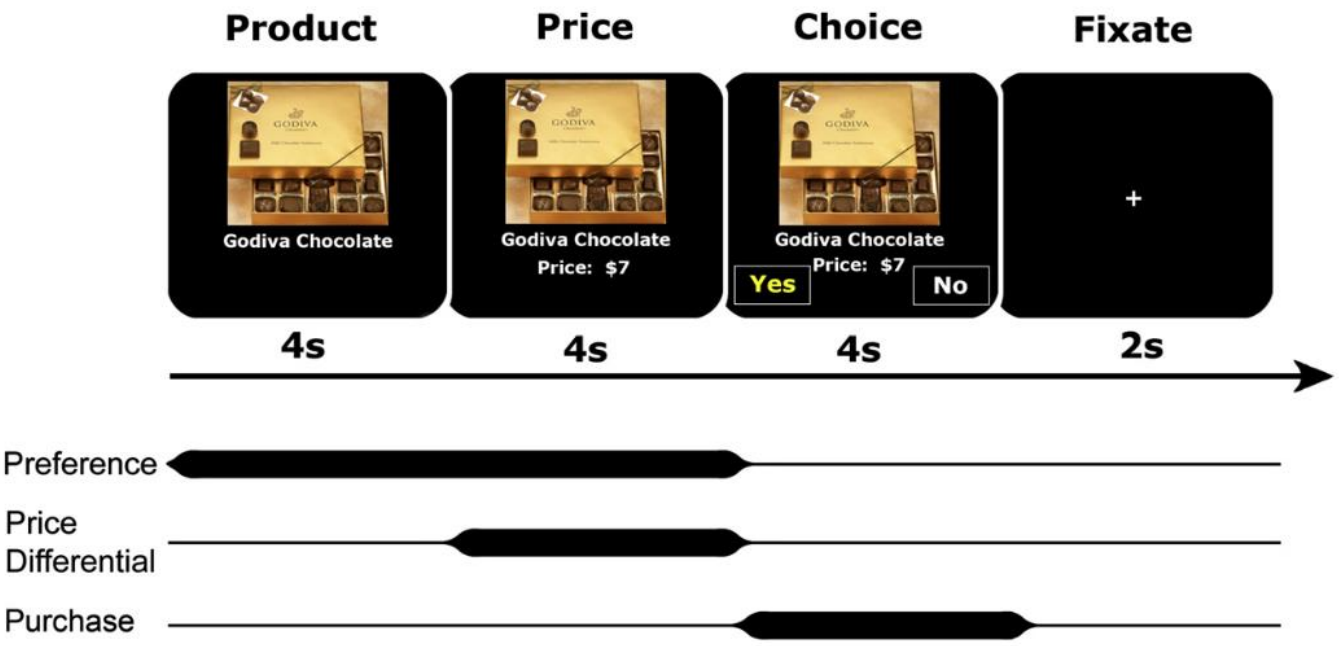

Figure 1. SHOP Task Trial Structure and Regressors
For task structure, subjects saw a labeled product (product period; 4 s), saw the product's price (price period; 4 s), and then chose either to purchase the product or not (by selecting either "yes" or "no" presented randomly on the right or left side of the screen; choice period; 4 s), before fixating on a crosshair (2 s) prior to the onset of the next trial. In regression models, preference was correlated with brain activation during the product and price periods, price differential was correlated with brain activation during the price period, and purchasing was correlated with brain activation during the choice period.

Role of NAcc

- Product preference activated the nucleus accumbens (NAcc)
- Excessive prices activated the insula and deactivated the mesial prefrontal cortex (MPFC) prior to the purchase decision.
- Activity from each of these regions independently predicted immediately subsequent purchases above and beyond self-report variables.
- These findings suggest that **activation of distinct neural circuits related to anticipatory affect precedes and supports consumers' purchasing decisions.**

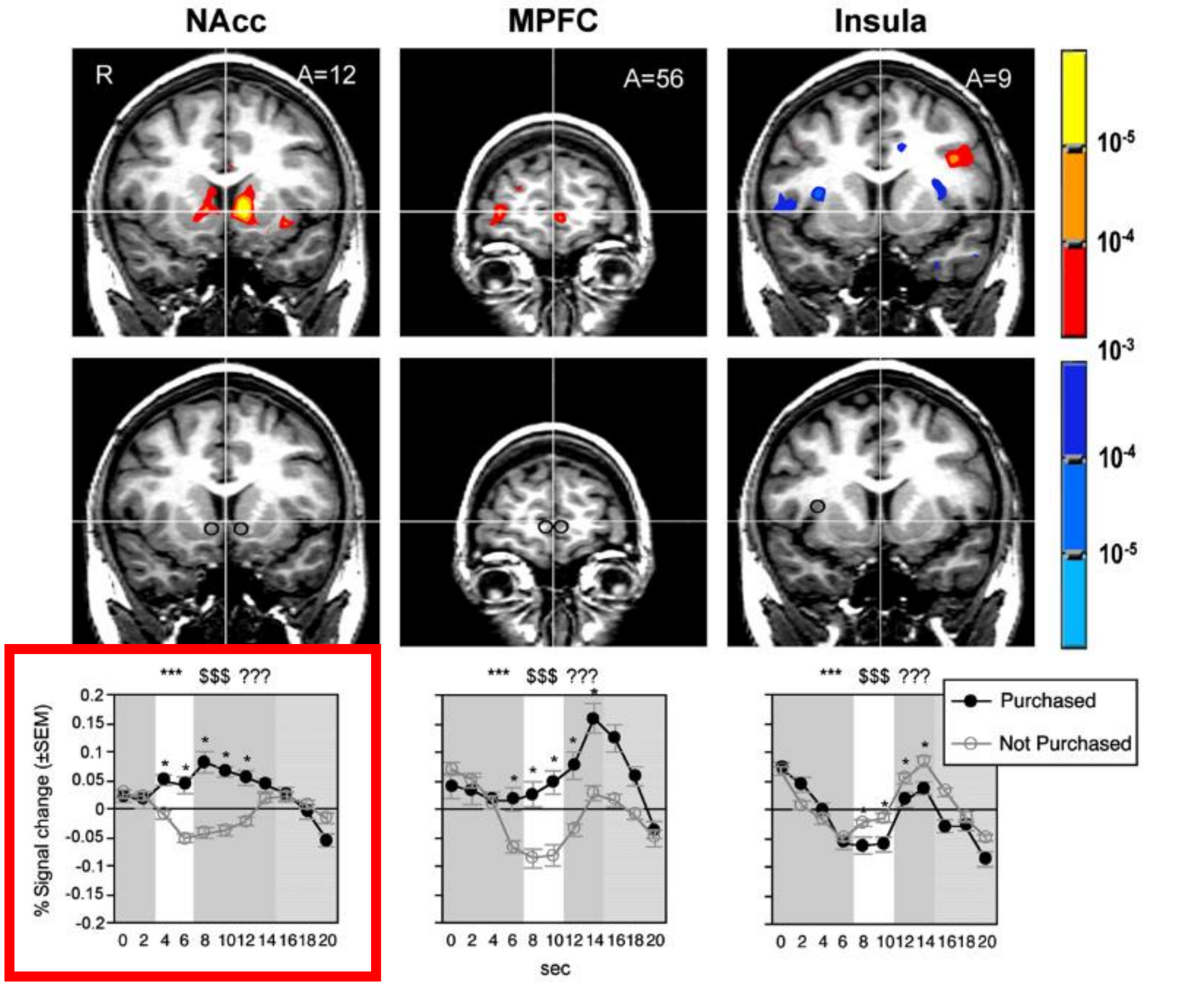

Figure 2. Correlated Activation, Volumes of Interest, and Corresponding Activation Time Courses
(Top row, left to right) Conjoined correlations of NAcc activation with preference during product and price periods; MPFC activation with price differential during the price period; insula activation with decision to purchase during the choice period (n = 26). (Middle row, left to right) Volumes of interest superimposed on structural images of the bilateral NAcc, bilateral MPFC, and right insula. (Bottom row, left to right) Bilateral NAcc activation time courses for trials in which products were subsequently purchased versus not; bilateral MPFC activation time courses; and right insula activation time courses (white, predicted divergence; ***, product period; $$$, price period; ???, choice period; all lagged/shifted right by 4 s; n = 26, *p < 0.05; error bars = SEM).

Role of NAcc

- In this study, the authors investigated preferences to different types of products
- It has been shown recently that **reward mechanisms** are involved in the regulation of social relations like dominance and social rank.
- Based on evolutionary considerations we hypothesized that **sportscars** in contrast to other categories of cars, e.g. limousines and small cars, are **strong social reinforcers** and would modulate the dopaminergic reward circuitry.
- N = 20 healthy male subjects were studied with fMRI while viewing photographs of different car classes followed by an attractivity rating.

Cultural objects modulate reward circuitry

Susanne Erk, Manfred Spitzer, Arthur P. Wunderlich,[1] Lars Galley[2] and Henrik Walter[CA]

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Received 22 October 2002; accepted 1 November 2002

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Sportscars Limousines Small Cars

Fig. 1. Picture stimuli. Example of photographs of sports cars, limousines and small cars as used in the experiment.

Role of NAcc

- Behaviorally sports cars were rated significantly more attractive than limousines and small cars

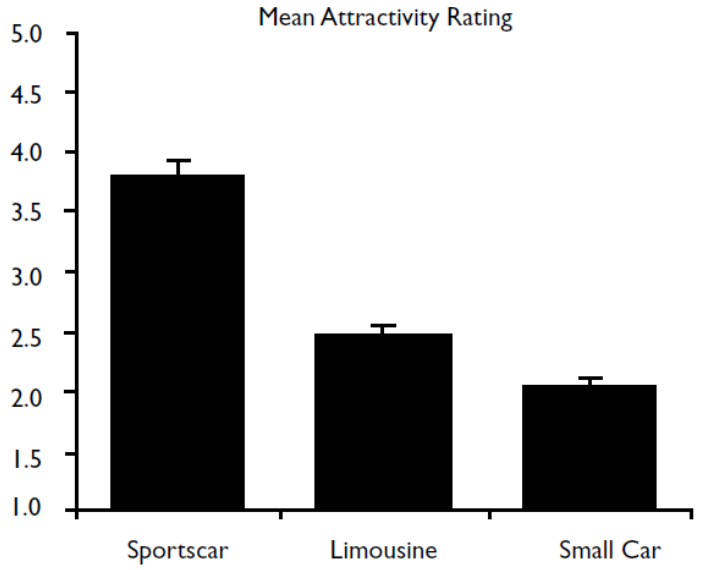

Fig. 2. Mean attractivity rating. Mean rating scores of sports cars, limousines and small cars as rated by the subjects during the fMRI experiment. Sports cars were rated significantly more attractive than limousines and small cars ($F(2,33) = 68.299$, $p < 0.0001$). Mean attractivity rating for sports cars 3.79 ± 0.14, limousines 2.46 ± 0.09, and small cars 2.03 ± 0.08.

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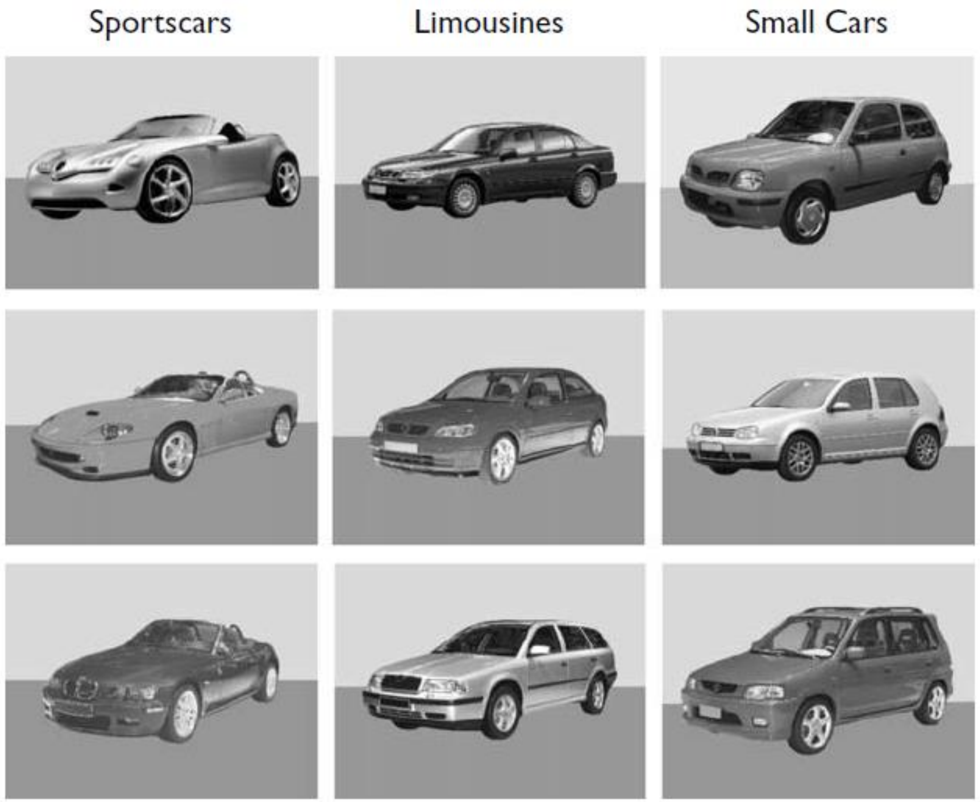
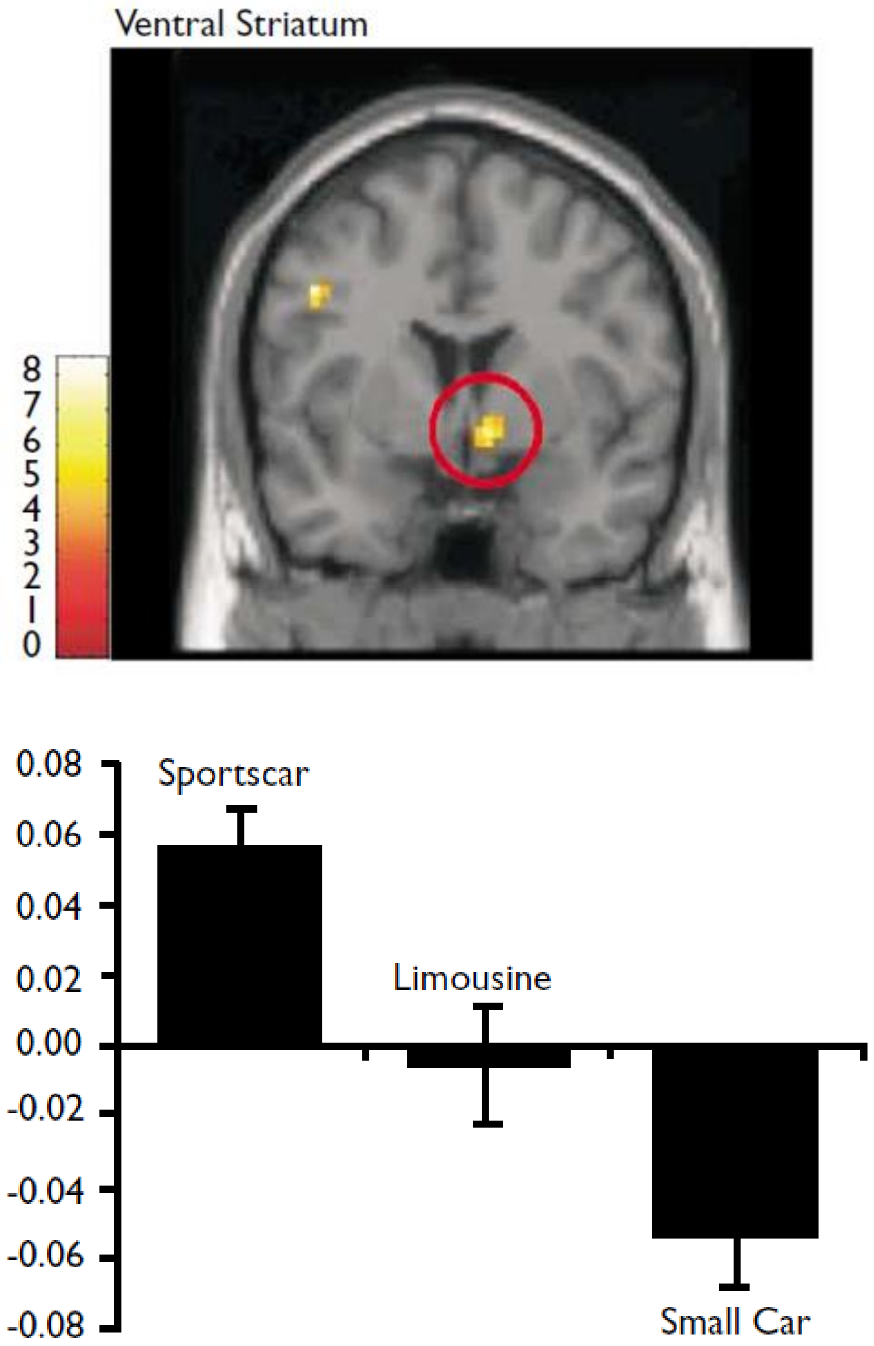


Fig. 1. Picture stimuli. Example of photographs of sports cars, limousines and small cars as used in the experiment.

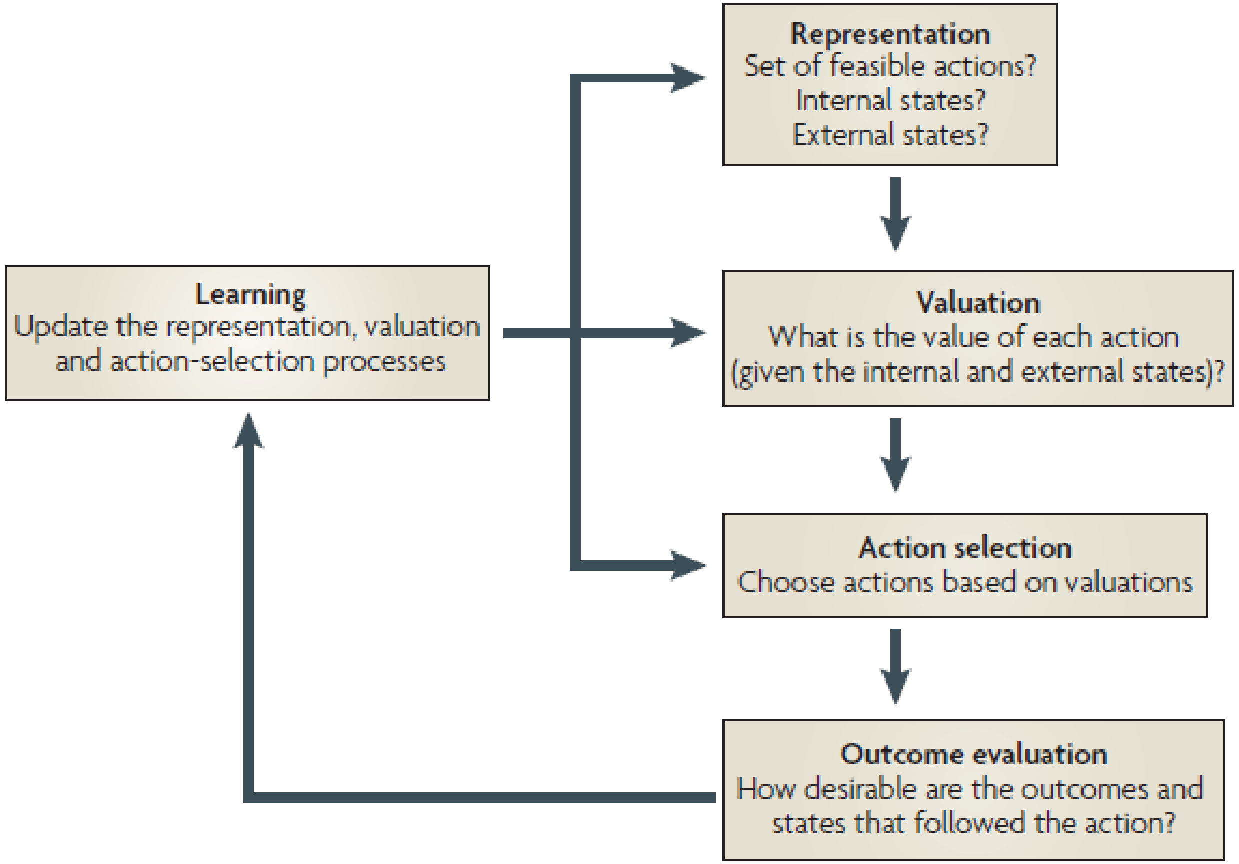
Role of NAcc

- fMRI results revealed significantly more activation in ventral striatum, orbitofrontal cortex, anterior cingulate and occipital regions for sports cars in contrast to other categories of cars.

- Dopamine system and NAcc are involved into the valuation process of decision-making.



Valuation based on different utilities



- Valuation process is more complicated in real life
- Valuation is influenced by learning
- Learning utility is the utility value updated, based on past experiences. The dopaminergic system is involved in learning utility (prediction errors signals).

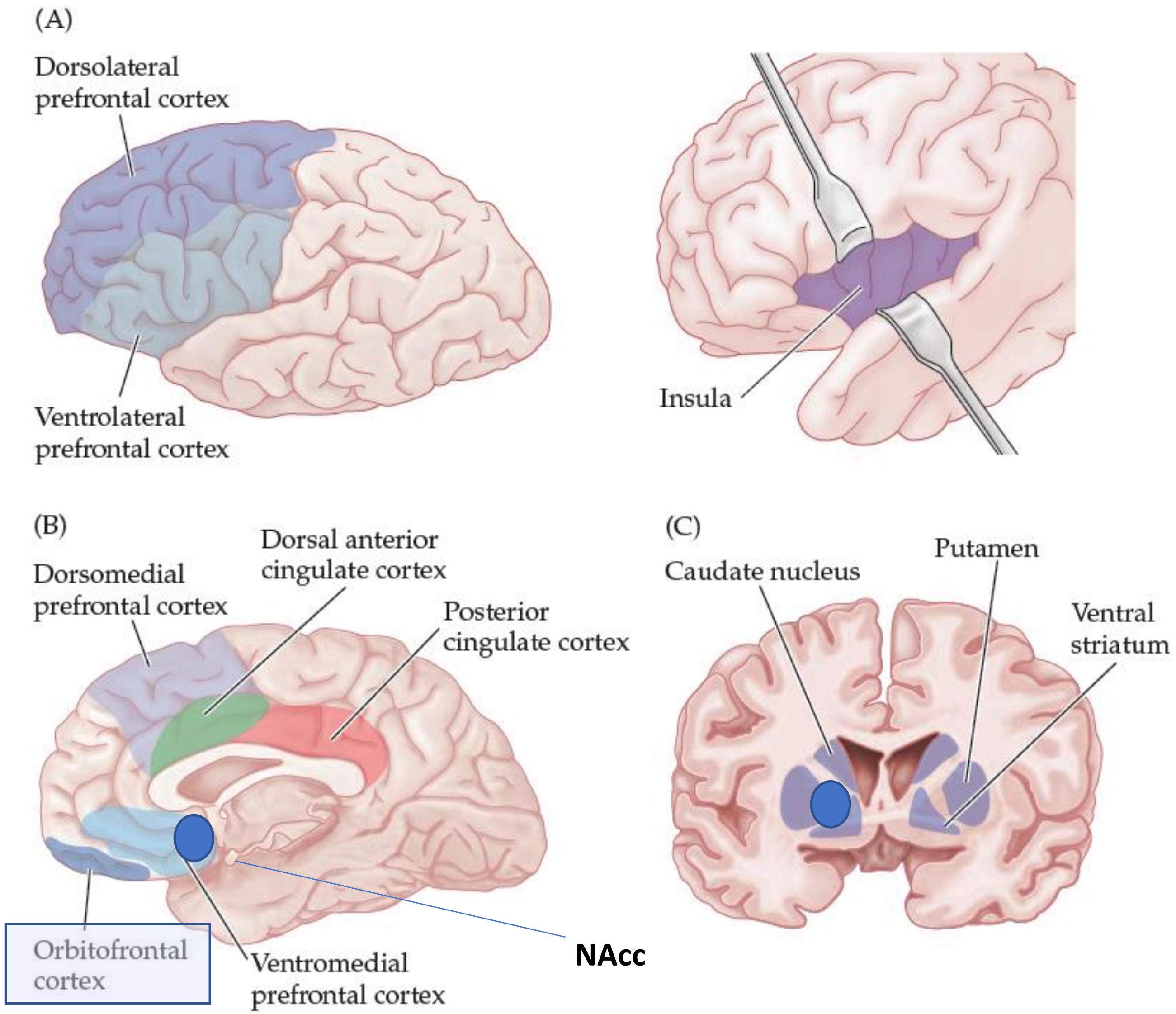
Summary

- A Sketch of the Relevant Circuitry
- Nucleus Accumbens (Nacc)
- **<u>Orbitofrontal</u> Cortex and Ventromedial Cortex: Evaluation of Options**
- Dorsolateral Prefrontal Cortex and the Planning and Organization of Behavior
- Cingulate Cortex and Learning from the Consequences of Behavior
- Ventrolateral Prefrontal Cortex and Self-Control

Role of orbitofrontal cortex

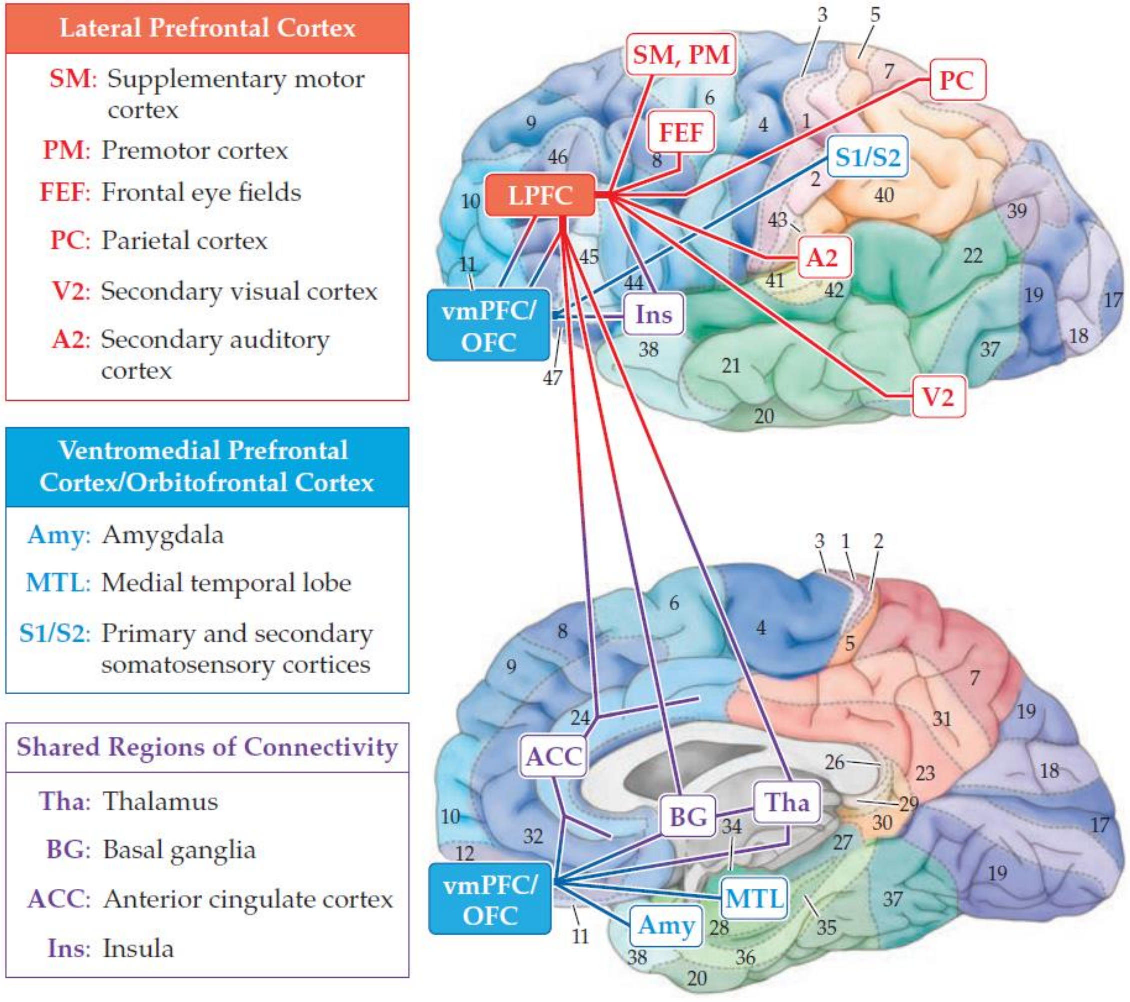
NAcc is involved in anticipated gain (magnitude and probability) and learning utility

OFC → Structure highly connected with the Nacc
Role: compare and integrate information related to the outcomes of a decision



Role of Orbitofrontal cortex

- The OFC **receives input from all of the major sensory modalities** (vision, audition, somatic sensation, olfaction, and gustation), giving it access to the information necessary to identify options.
- Unlike other prefrontal regions, however, the OFC has **few motor connections**, consistent with the idea that the OFC provides inputs to systems that themselves inform the selection and execution of behavior.
- Furthermore, the OFC **receives inputs from the hippocampus** and adjacent regions in the medial temporal lobe that are involved in memory storage and retrieval. These inputs presumably provide information about prior experiences to improve estimates of value.
- Finally, the OFC **receives inputs from reward-related dopamine neurons** in the midbrain that help shape associations among objects, actions, and their consequences



Role of Orbitofrontal

- Computation and comparison of values take place within prefrontal regions, including the OFC, the vmPFC
- **Direct evidence for the role of the OFC in evaluation is fairly strong**

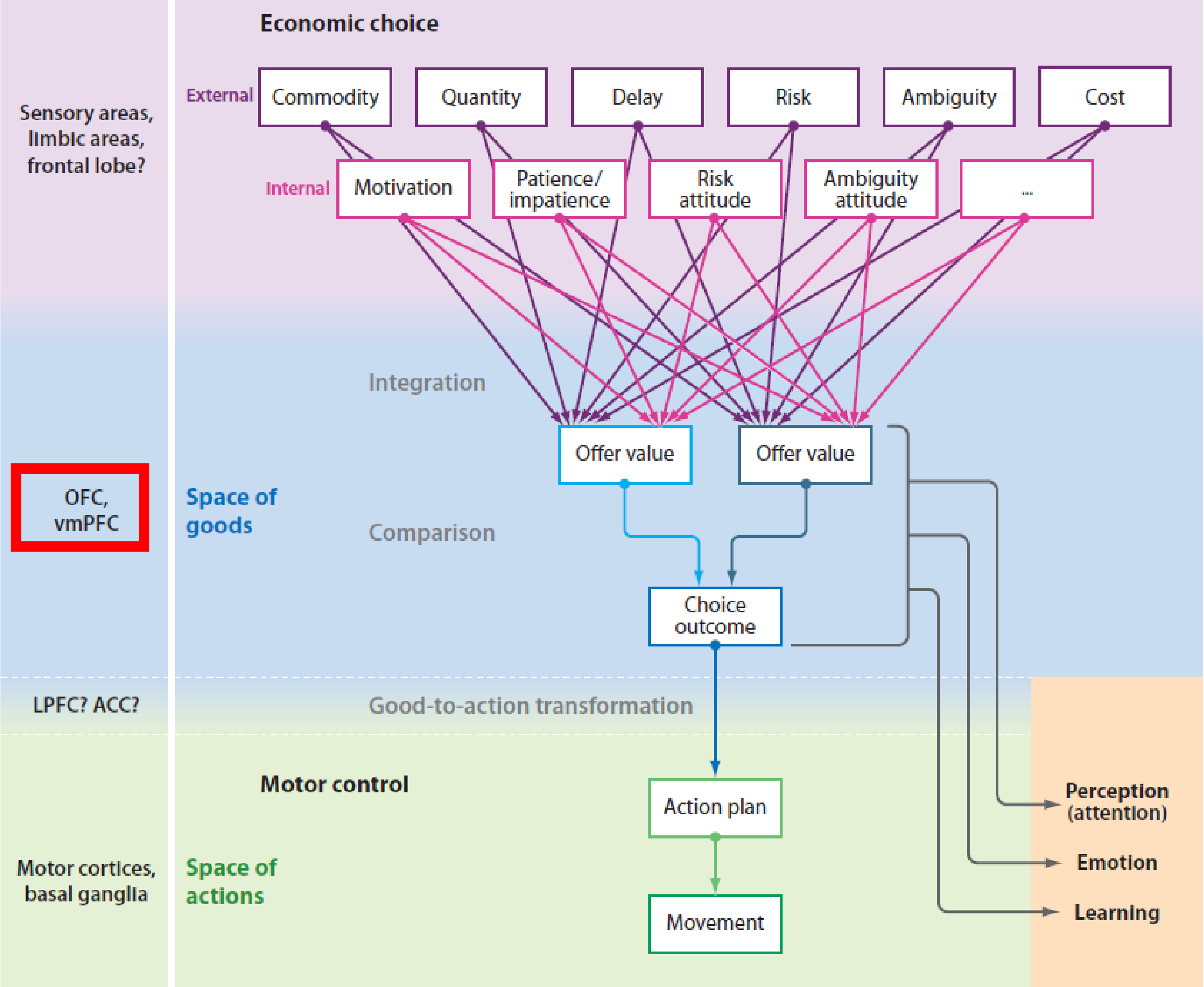


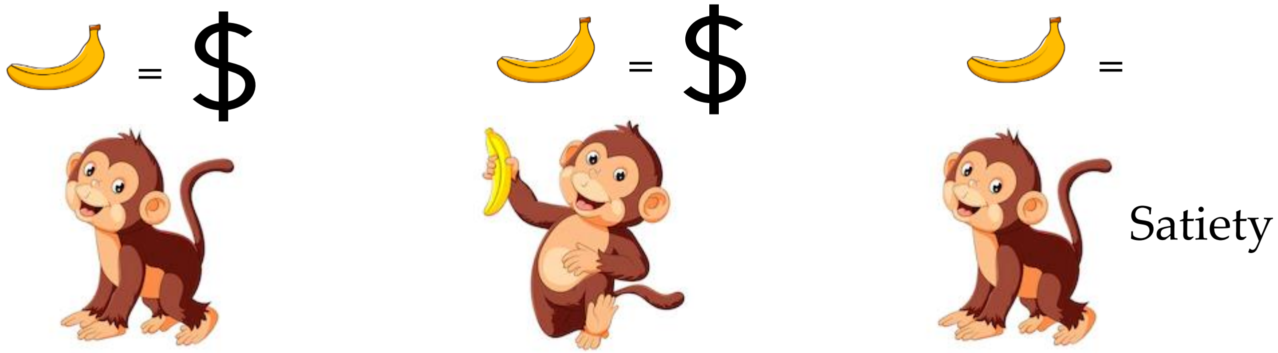
Figure 1

Good-based model. The value of each good is computed integrating multiple determinants, of which some are external (e.g., commodity, quantity, etc.) and others are internal (motivation, (im)patience, etc.). Offer values of different goods are computed independently of one another and then compared to make a decision. This comparison takes place within the space of goods. The choice outcome (chosen good, chosen value) then guides an action plan through a good-to-action transformation. Values and choice outcomes also inform other brain systems, including sensory and motor systems (through attention and attention-like mechanisms), associative learning (e.g., through mechanisms of reinforcement learning), emotion (including autonomic functions), etc. Abbreviations: orbitofrontal cortex (OFC), ventromedial prefrontal cortex (vmPFC), lateral prefrontal cortex (LPFC), anterior cingulate cortex (ACC).

Padoa-Schioppa. Ann. Rev Neurosci, 2011

Role of Orbitofrontal cortex

- When monkeys choose among options varying in reward amount, reward type, and probability of reward delivery, **firing rates of some neurons in the OFC track individual preferences** for a particular option, a variable known as subjective value



- When a monkey that likes bananas is fed them to satiety, the sensory properties of bananas remain the same but **their value** to the monkey is **reduced**
- **Satiety is accompanied by a reduction in the firing rates of OFC neurons** in response to more bananas, implying that the OFC encodes the subjective value of a food and not just its sensory properties.

Role of Orbitofrontal cortex

- Evidence for the evaluative role of the OFC also comes from neuroimaging studies.
- A study on the human enjoyment of wine: enjoyment is related to factors that do not affect wine taste but other factors, such as wine costs
- Expensive wine tastes better

- This change in appeal is reflected in **changes in hemodynamic activity in the OFC**, suggesting that the activity mediates the change in enjoyment associated with price

Role of Orbitofrontal cortex

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Nature. 2006 May 11; 441(7090): 223–226. doi:10.1038/nature04676.

Neurons in Orbitofrontal Cortex Encode Economic Value

Camillo Padoa-Schioppa and **John A. Assad**
Department of Neurobiology, Harvard Medical School

Too complex, just remember the role of the OFC

- In economic choice, there is no intrinsically "correct" answer; the choice depends on subjective preferences.
- In this study, authors examined trade-offs between **commodity** (juice type) and **quantity**.
- In our experiments, monkeys choose between two types of juice (A and B) offered in different amounts. For example, in the session shown in figure 1a, the monkey chooses between 1 drop of water (juice A) and unsweetened Kool-Aid (juice B B). In figure 1b: Offer types include 0B:1A, 1B:2A, 1B:1A, 2B:1A, 3B:1A, 4B:1A, 6B:1A, and 10B:1A, and the "forced choices" 0B:1A and 3B:0A.
- The monkey indicated its choice with an eye movement

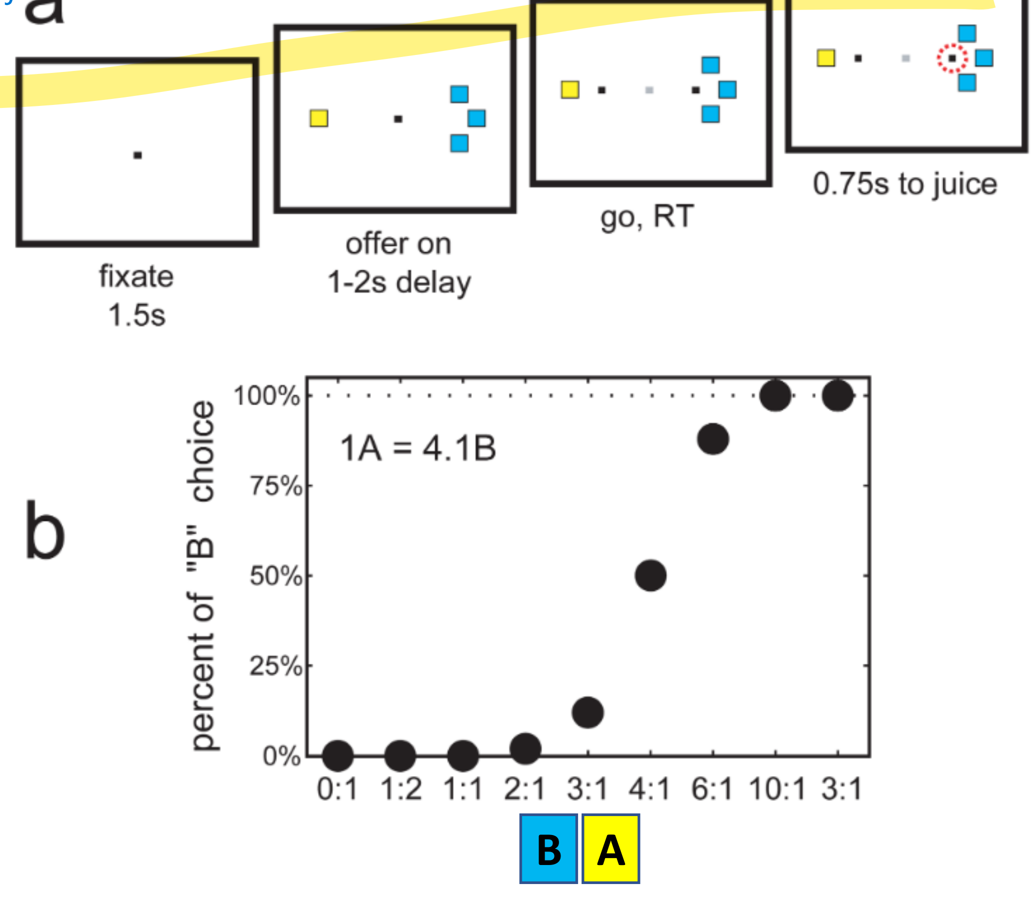

Figure 1.
Experimental design. **a.** Trial structure (see Methods). **b.** Example of behavioral choice pattern. The plot shows the percentage of trials in which the monkeys chose juice B (y-axis) for various offer types (x-axis). A sigmoid fit provides the measure of the relative value n*=4.1.

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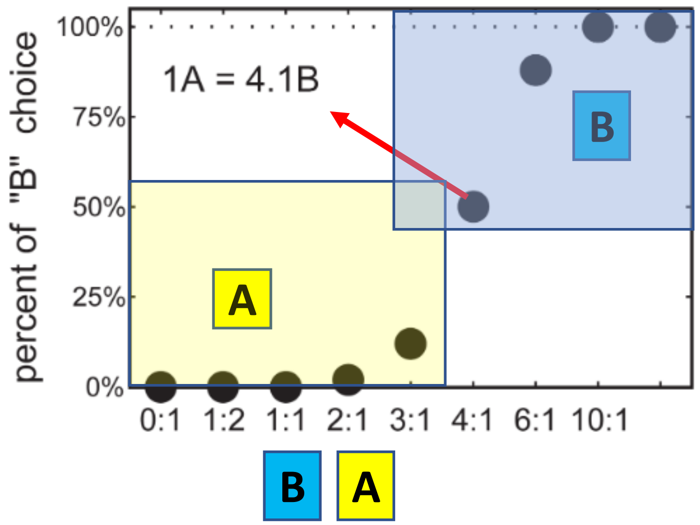
When offered one drop of juice A versus one drop of juice B (offer 1A:1B), the animals chose juice A. This is true also in the condition 3:1.

This situation is reversed when 4 drops of B are offered → Thus the monkey assigned to 1A a value roughly equal to the value it assigned to 4B.

B is chosen when the amount of drops vary consistently (3:1).

b



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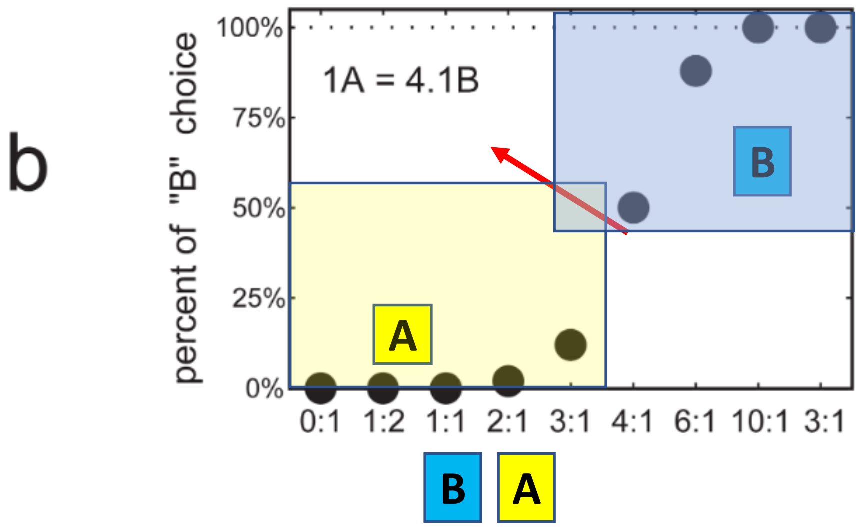
The relative value is 4.1.

The monkey was roughly indifferent between 1A and 4B.

A sigmoid fit indicated, more precisely, that 1A = 4.1B. The relative value (4.1 here) is a subjective measure in multiple senses.

1. First, it depends on the two juices.
2. Second, given two juices, it varies for different individuals.
3. Third, for any individual and two given juices, it varies depending, for example, on the motivational state of the animal (thirst).

Thus, to examine the neural encoding of economic values, it is necessary to examine neural activity in relation to the **subjective values measured concurrently**.



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Role of Orbitofrontal cortex

Neurobiology of Economic Choice: A Good-Based Model

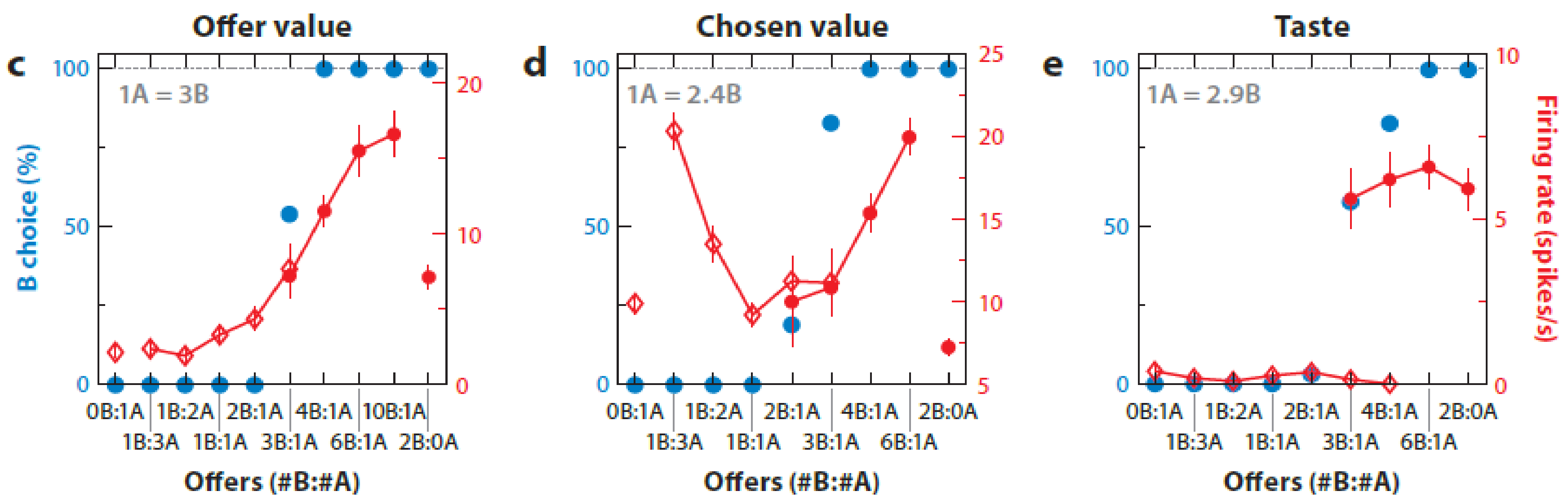
Camillo Padoa-Schioppa

Department of Anatomy and Neurobiology, Washington University in St. Louis, St. Louis, Missouri 63110; email: camillo@wustl.edu

On this basis, the authors computed a variety of value-related variables, which were then used to interpret the activity of neurons in the **OFC**. In particular, the analysis showed that neurons in this area encode three variables:

1) offer value (the value of only one of the two juices),
2) chosen value (the value chosen by the monkey in any given trial),
3) and taste (a binary variable identifying the chosen juice).

Role of Orbitofrontal cortex



Blue circles indicate the behavioral choice pattern (*relative value in the upper left*)

Red symbols indicate the neuronal firing rate.

- **Hollow red diamonds** refer to trials in which the animal chose **juice A**
- Filled red circles and refer to trials in which the animal chose juice B.

c) OFC neurons encoding the offer value, the variable on which choices were presumably based.

A linear relationship exists between the activity of the cell and the quantity of juice B offered to the monkey

d) OFC neurons encoding the chosen value. A linear relationship exists between the activity of the cell and the value chosen by the monkey in each trial. For this session, 1A = 2.4B.

The activity of the cell was low when the monkey chose 1A or 2B, **higher** when the monkey chose 2A or 4B, and **highest** when the monkey chose 1A or 6B.

Neurons encoding the chosen value are thus identified on the basis of the relative value of the two juices. Higher activity when one option is clearly better than another.

e) OFC neuron encoding the **taste**. The activity of the cell is binary depending on the chosen juice but independent of its quantity

Role of Orbitofrontal cortex

- The **relationship** between activity in the **OFC** and **personal preferences** is so robust that measures of brain activity in the OFC can be used to **predict purchasing behavior** in simulated marketplaces over an array of products, including snack foods, beverages, and ads that feature attractive people.
- Indeed, a remarkable feature of the OFC is its apparent ability to contribute directly to decisions about so many different things, ranging from which soda to buy from a vending machine to which college to attend.
- This flexibility has led to the proposal that the OFC and/or the ventromedial prefrontal cortex (vmPFC) make use of a universal value "format" that allows comparison of any set → COMMON CURRENCY THEORY → maybe simplistic!

Role of Orbitofrontal cortex

- Actually making a choice occurs after evaluation and requires **active maintenance of the values** of two or more options. This process seems likely to occur in the OFC as well, or in the neighboring ventromedial PFC, a structure with similar neuroanatomy and function as the OFC

- Neurons in both regions show systematic changes in firing when the values of multiple options are maintained in short-term memory.

Role of Orbitofrontal cortex

- Es. Choose car → brain must make separate comparisons and use the results to make a decision
- <u>**Lesion**</u> → deficits in comparing the values of disparate options → less efficient with more options

PRICE

Styling

Parking

Gas mileage

Role of Orbitofrontal cortex

- OFC integrates multiple sources of information regarding the reward outcome and it produced a value signal.

- OFC supervises NAcc

- OFC value signal can be transmitted to dorsolateral prefrontal cortex (DLPFC) to plan and organize behaviour toward obtaining the outcome.

- OFC is highly interconnected to the neighborging ventromedial PFC (**vmPFC**)

Summary

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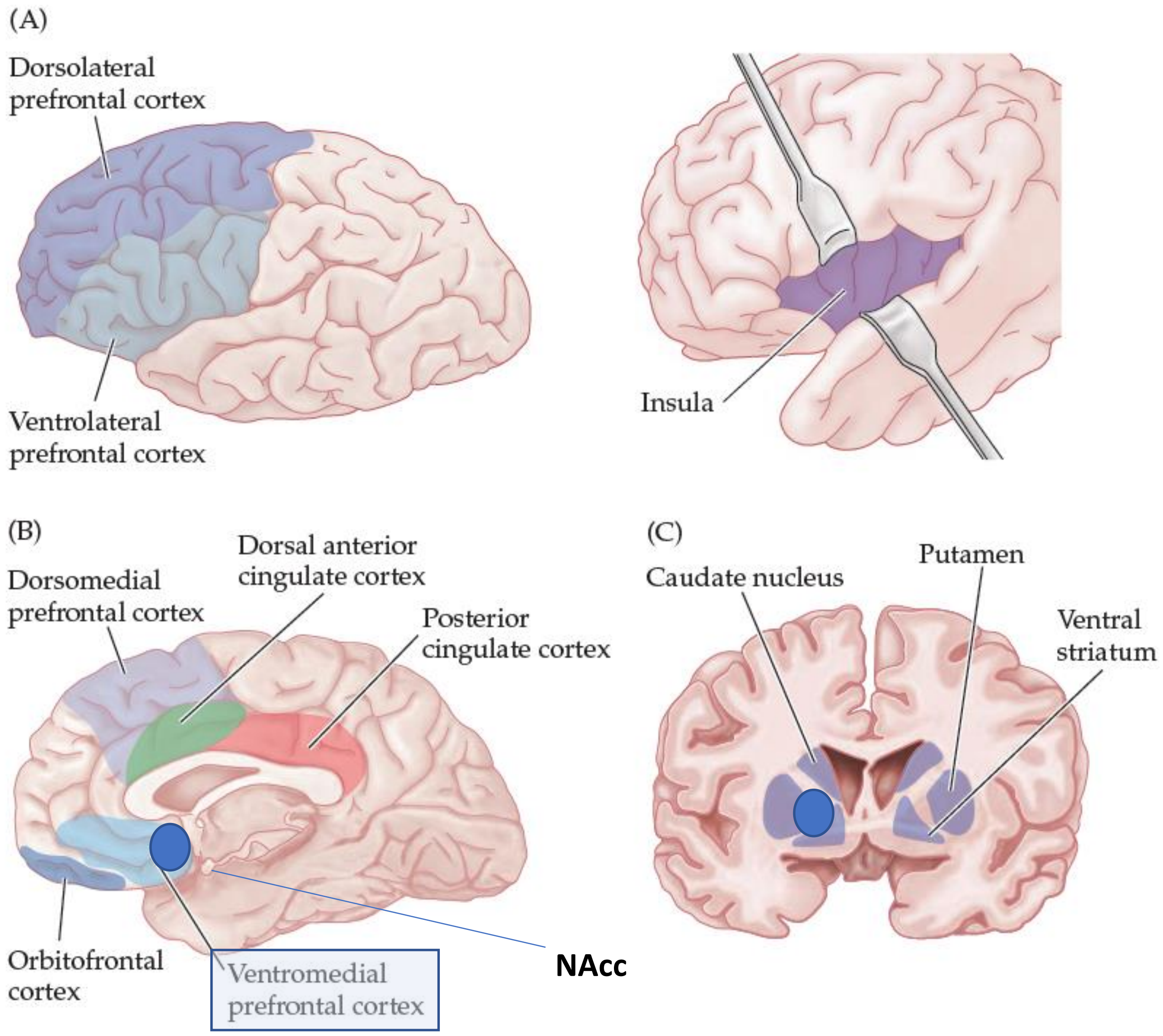
- Cingulate Cortex and Learning from the Consequences of Behavior
- Ventrolateral Prefrontal Cortex and Self-Control

Role of ventromedial cortex

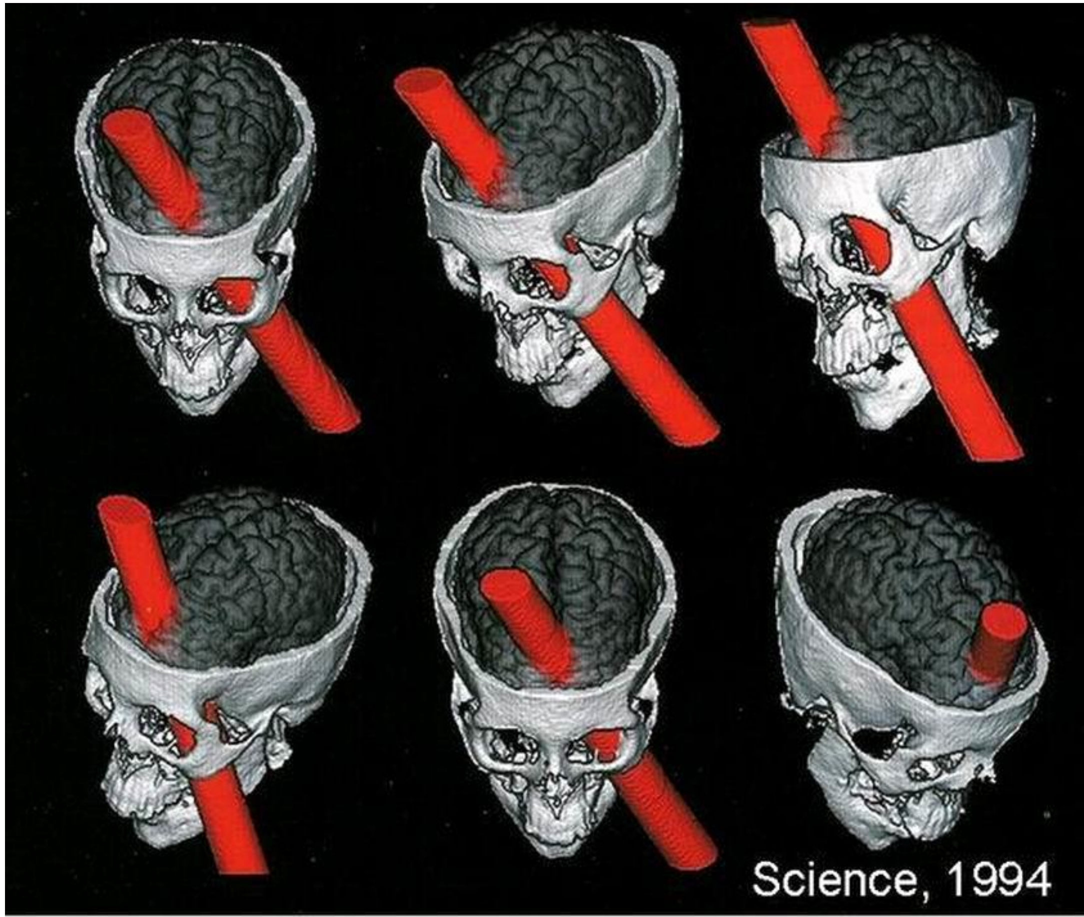
vmOFC → Structure highly connected with OFC

Role: assign value to different options (similar to OFC) → chose reward → moral judgement

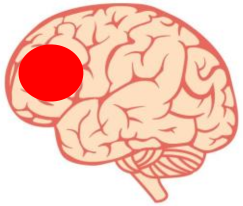


P. Gage (1823–1860)

- He lost a portion of his prefrontal cortex
- He survived but his behavior, his decision-making process dramatically changed.
- He became a very emotionally unstable person.
- He got a lot of problems in social interactions.
- He lost his job.
- So, the way he made social decisions, the way he behaved, changed.



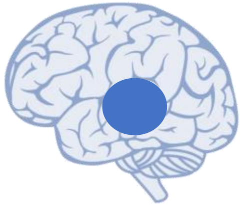
How to study "lesions"

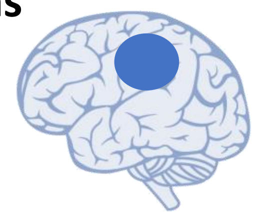


CONTROL GROUPS

Healthy volunteers

Patients with
different brain
lesions

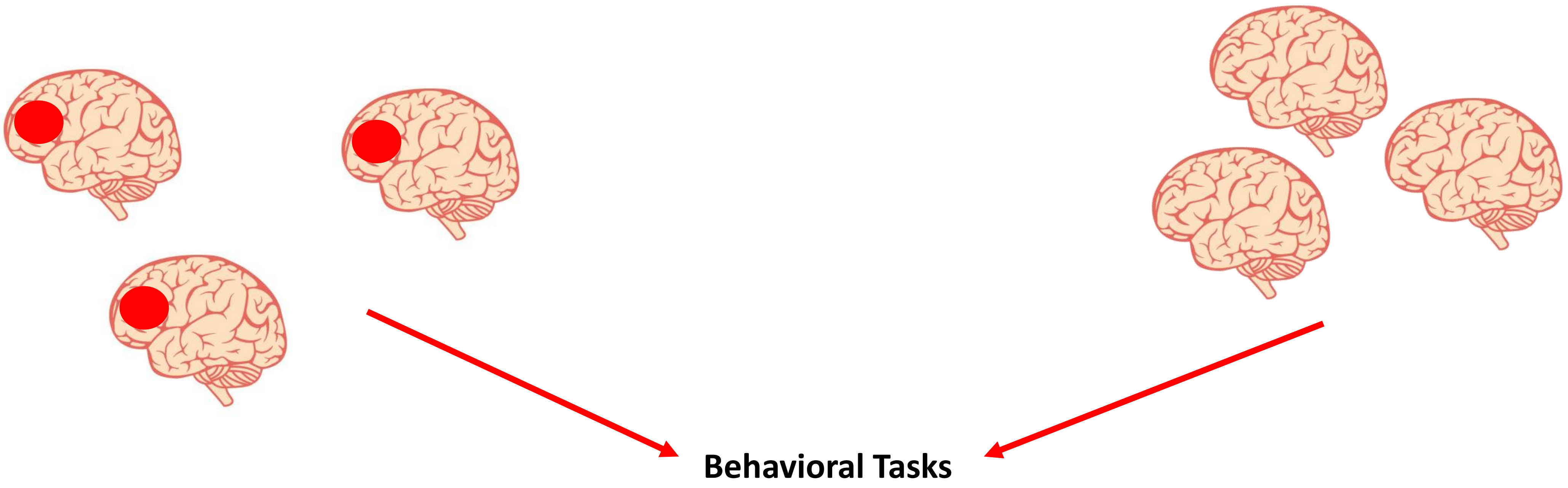




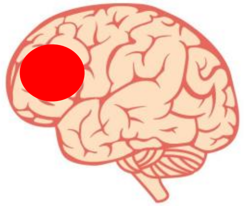
Behavioral Tasks

COMPARE RESULTS and
EXPLAIN DIFFERENCES

Patients with vmPFC impairment

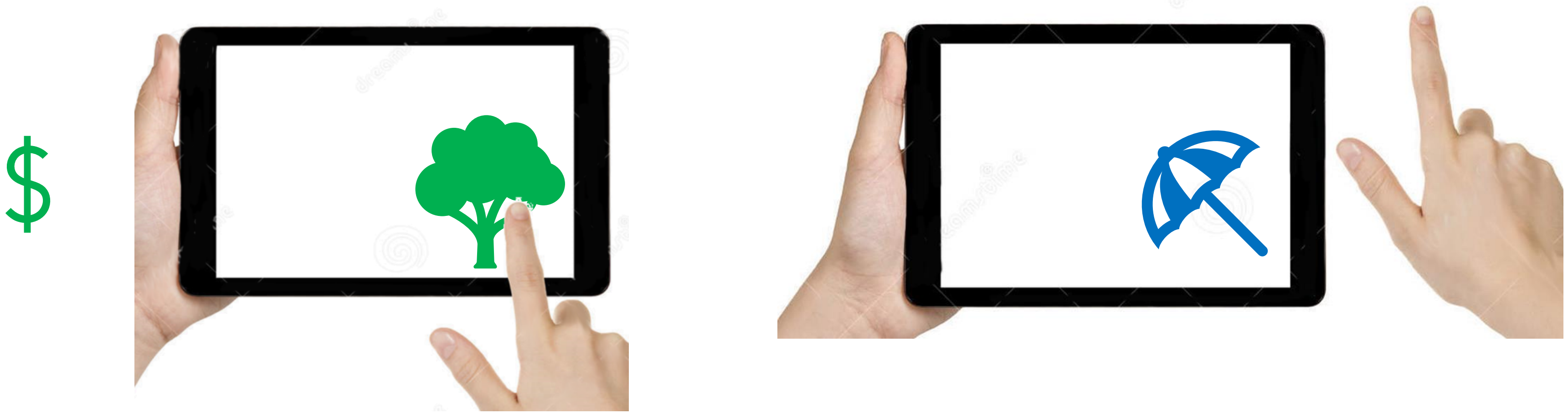


1) VM patients develop severe **impairments in personal and social decision making** in spite of otherwise largely preserved intellectual ability
2) After the onset of their prefrontal cortex lesion, they begin to have difficulties in learning from previous mistakes → repeated engagement in decisions that lead to negative consequences →MYOPIA for the FUTURE →guided by actions with immediate prospects



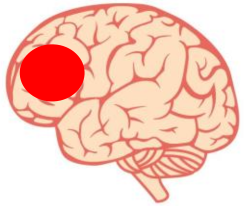
Patients with vmPFC impairment

- How to study the neural mechanisms underlying this behaviour?
- STUDY stimulus-reward learning (Rolls et al., 1994; Rolls, 2000)



- In this paradigm, subjects obtained a reward ($) touching a stimulus when It appeared on a video screen, but they had to withhold the response if a different stimulus appeared.

Rolls et al., 1994; Rolls, 2000



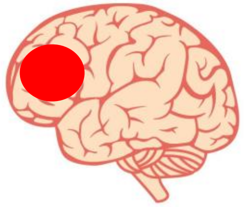
Patients with vmPFC impairment

- After different pairings (stimulus-reward)

- The reward contingencies were reversed

Rolls et al., 1994; Rolls, 2000

Patients with vmPFC impairment



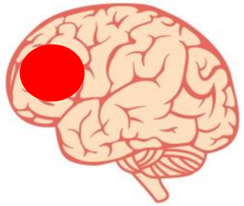
- Patients with orbitofrontal cortex impairment were **unsuccessful** in making the shift in behaviour, although they were able to report that the contingencies had changed.

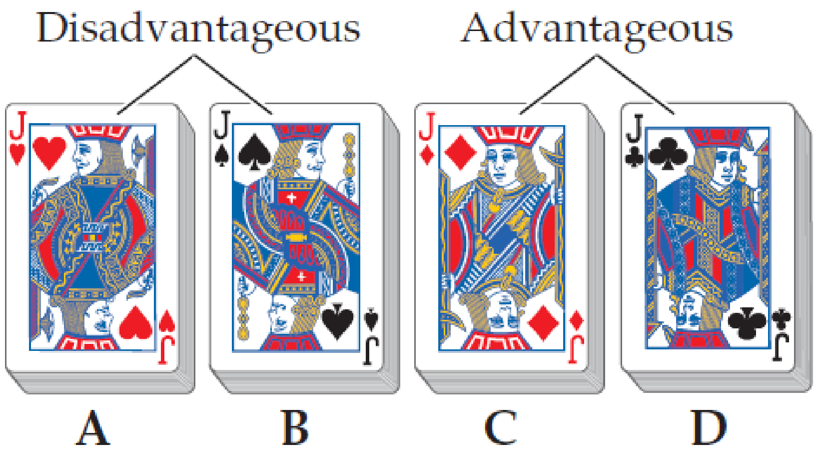
$ 

- <u>Conclusion</u>: orbitofrontal cortex is critical for evaluating the associations of environmental stimuli with reinforcement.

Rolls et al., 1994; Rolls, 2000

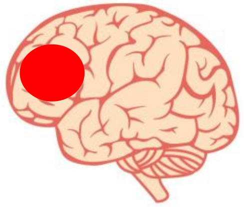
Patients with vmPFC impairment

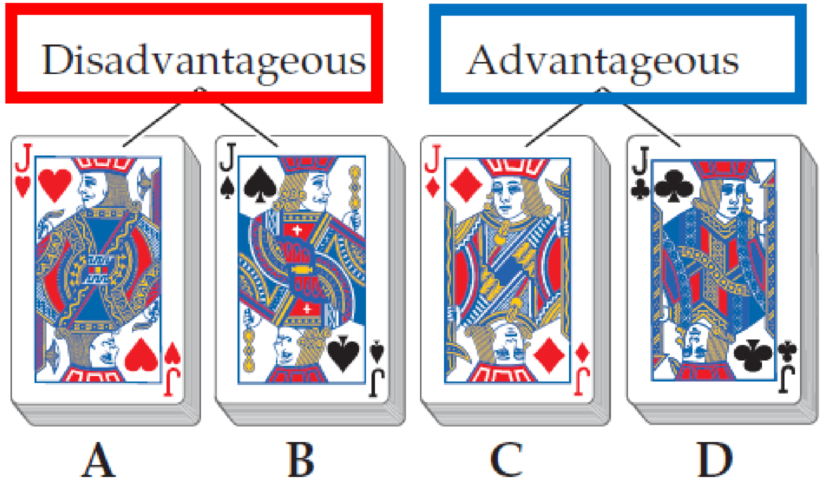




- In order to detect and measure in the lab the decision-making impairment of VM lesion patients → it has been developed a GAMBLING TASK (IOWA GAMBLING TASK) which resembles the decisions made in real life in terms of reward, punishments and uncertainty of outcomes.
- In this task, individuals draw cards from one of four decks. Each card is associated, in turn, with winning or losing money, and individuals naturally try to maximize their winnings.

Patients with vmPFC impairment





Chose a card from one of the 4 decks:

1) From decks A and B →choosing a card is followed by a **high gain (+100 $ per trial)** of money BUT… the selection of a card is followed by a **high penalty** at unpredictable points
2) From decks C and D → the immediate gain is **smaller (+50$ per trial)** BUT also the future loss

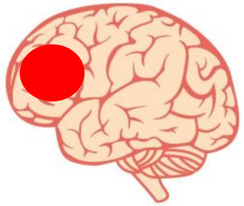
Original Task (ABCD)

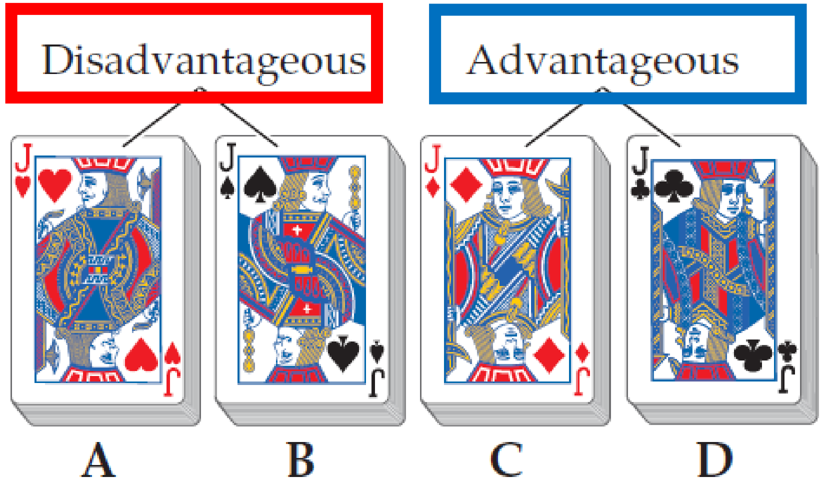
Deck	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
A (+100)			-150		-300		-200		-250	-350		-350		-250	-200		-300	-150				-300		-350		-200	-250	-150			-350	[illegible]								
B (+100)	0	0		0		0			-1250		0	0		-1250		0	0				-1250		0	0		0		0			0	[illegible]								
C (+50)			-50		-50		-50		-50	-50		-25	-75				-25	-75		-50				-50	-25	-50			-75	-50										-75
D (+50)	0		0			0	0			-250	0	0			0				0	-250		0			0	0	0		-250											

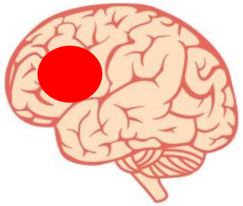
+4000
- 5000
→ -1000

+2000
- 1000
→ 1000

Patients with vmPFC impairment

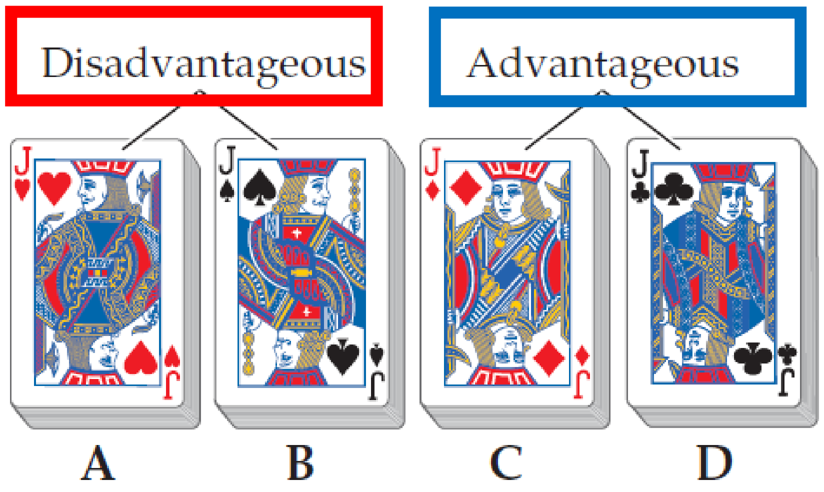




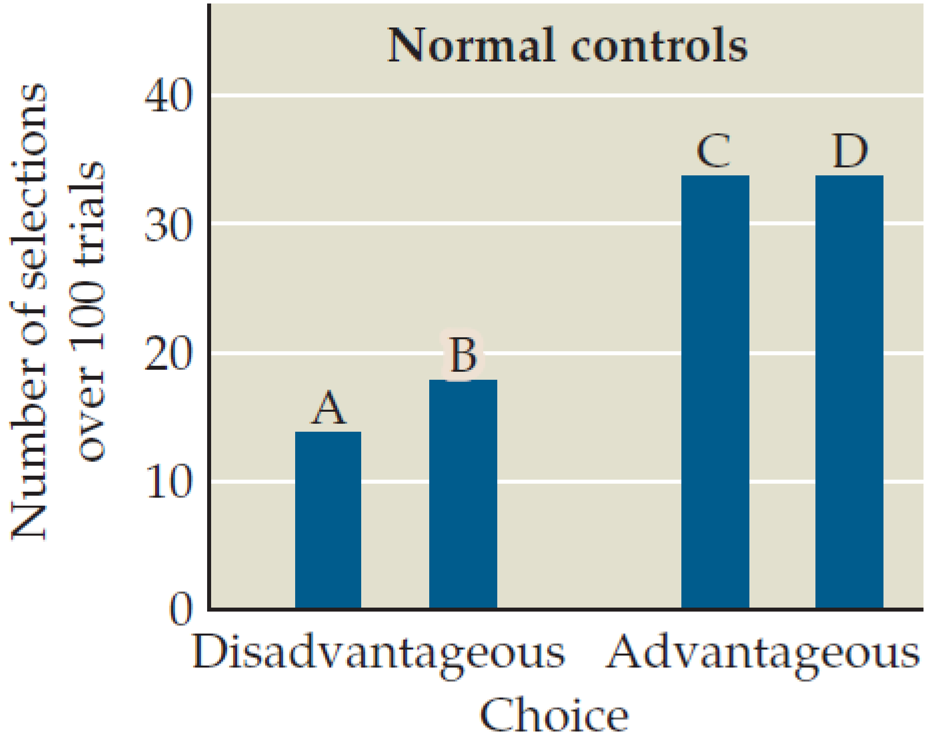


After sampling and encountering losses in each deck, normal subjects: 1) begin to AVOID the disadvantageous decks
2) produce anticipatory skin conductance responses before selecting A and B

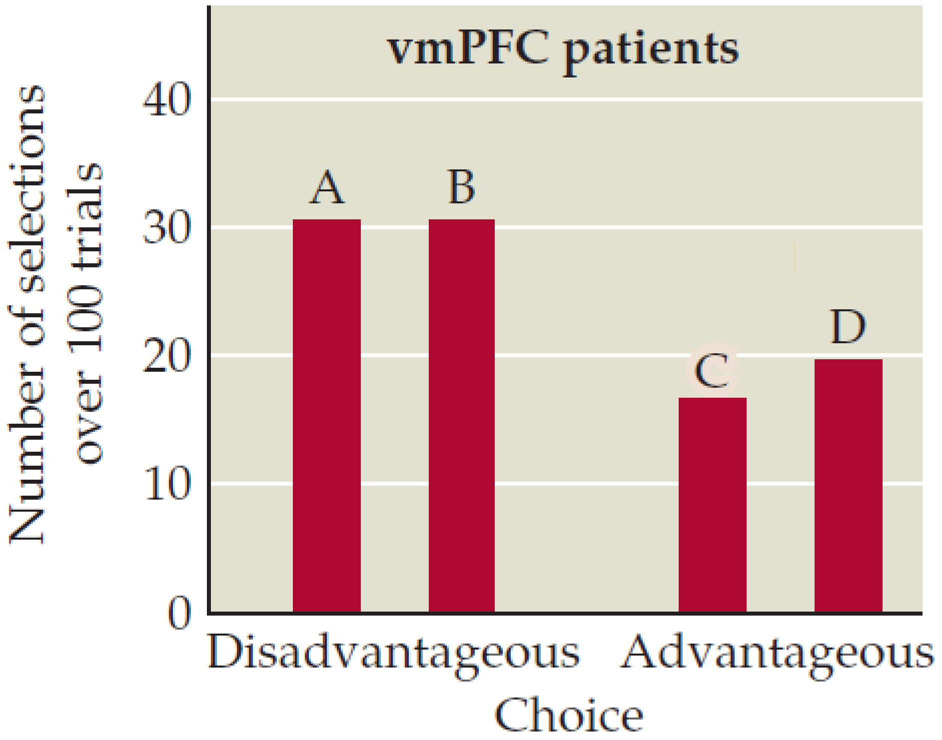
By contrast, VM patients **continue to select more cards from the disadvantageous decks** and they fail to produce any anticipatory skin conductance responses



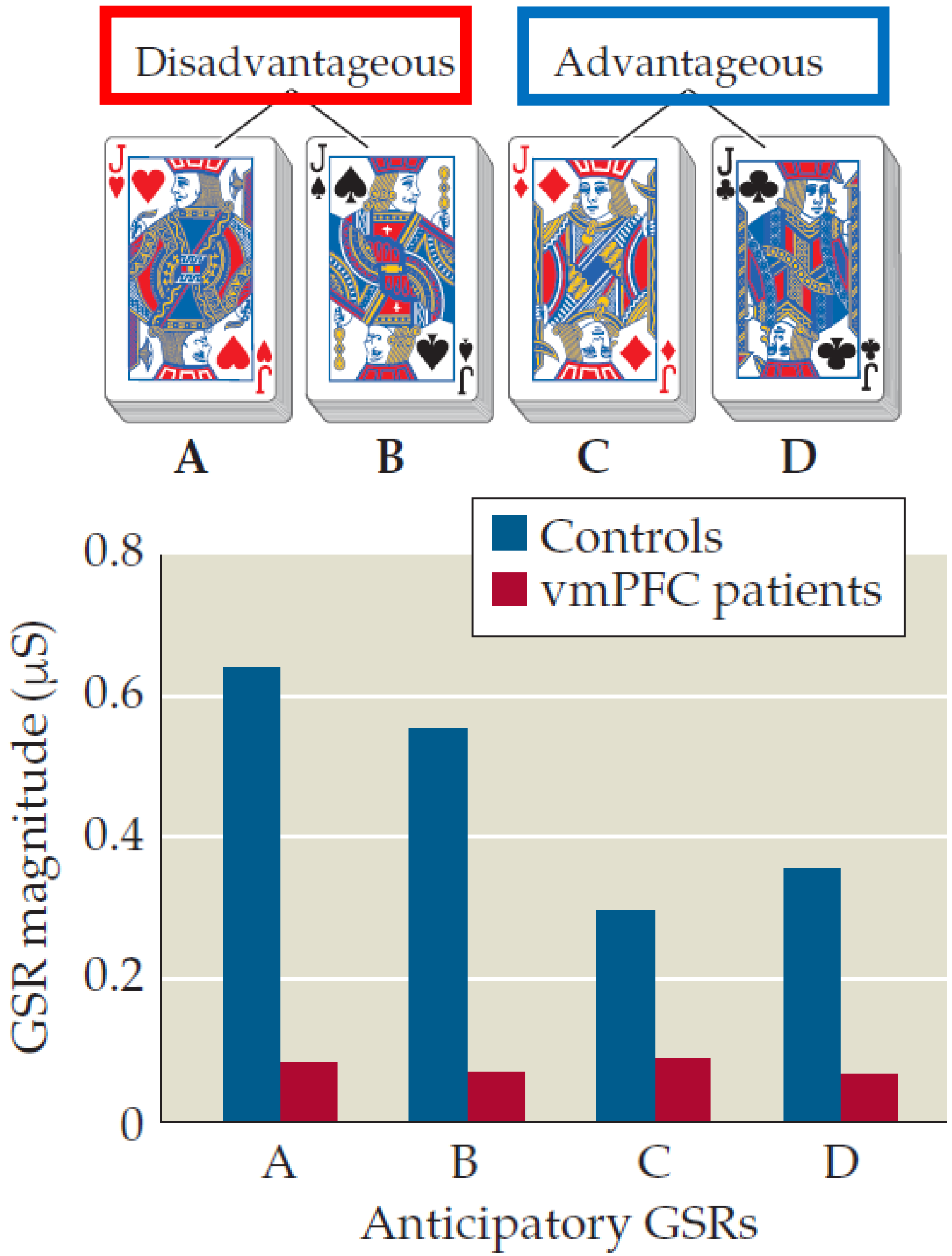
Disadvantageous
Advantageous
A
B
C
D



Normal controls
Number of selections over 100 trials
40
30
20
10
0
A
B
C
D
Disadvantageous
Advantageous
Choice

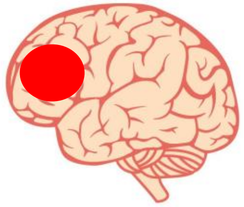


vmPFC patients
Number of selections over 100 trials
40
30
20
10
0
A
B
C
D
Disadvantageous
Advantageous
Choice



Disadvantageous
Advantageous
A
B
C
D
Controls
vmPFC patients
0.8
0.6
0.4
0.2
0
GSR magnitude (μS)
A
B
C
D
Anticipatory GSRs

Patients with vmPFC impairment



Brain (2000), **123**, 2189–2202

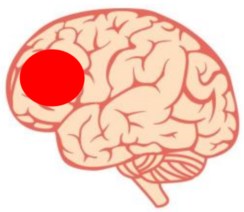
Characterization of the decision-making deficit of patients with ventromedial prefrontal cortex lesions

Antoine Bechara, Daniel Tranel and Hanna Damasio

Experimental questions:

1) Why do VM lesion patients fail to avoid the disadvantageous decks?
2) Can performance on the gambling task be normalized in VM patients if adverse future consequences are increased?

Patients with vmPFC impairment



Experimental questions:

1) Why do VM lesion patients fail to avoid the disadvantageous decks?

Possibility 1: HYPERSENSIBILITY to REWARD

- The prospect of a large immediate gain outweighs any prospect of future loss

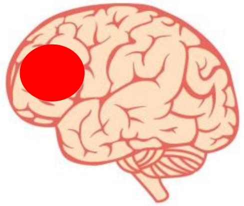
Possibility 2: INSENSITIVITY to PUNISHMENT

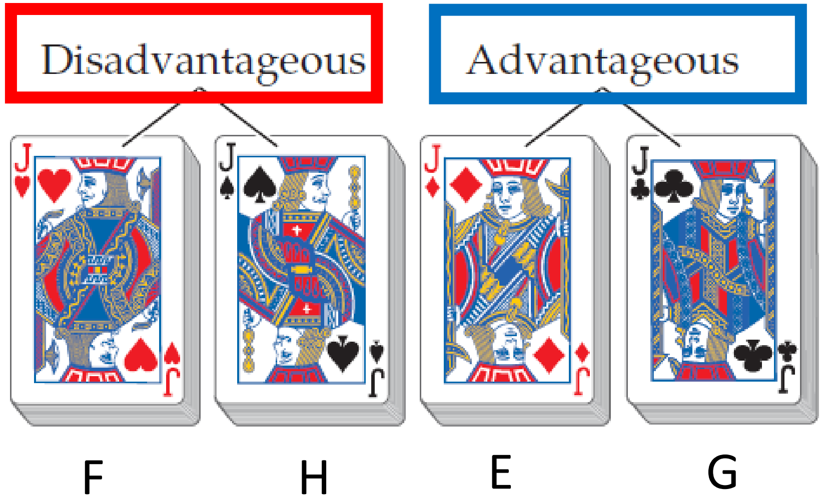
- The prospect of a large loss cannot override any prospect of gain

Possibility 3: INSENSIBILITY to FUTURE consequences (positive or negative)

- Patients are oblivious to the future and completely guided by the present

Patients with vmPFC impairment





Variant of the original gambling task in which the order of reward and punishment has been reversed (punishment immediate and reward delayed):

1) From decks E and G →choosing a card is followed by a **high** immediate **punishment (-100$ per trial)** but **<u>higher</u>** future **reward (+1000$ after 40 trials)**
2) From decks F and H → the immediate punishment is **<u>smaller</u> (-50 $ per trial)** BUT also the future gain

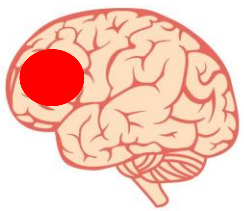
Variant Task (EFGH)

Deck	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
E(-100)	0		1250	0		0		0			1250			0		0	0			0	1250		0		0		0	0			0									
F(-50)				25	50			75	25	75	50		25			25	75			75				25	75	50			75	25										
G(-100)		350		250		300	200		150													300		350		150	200	250			150	200	350				200	350		
H(-50)	0		0			0	0	250			0														0	0	0		0	250			0	250		0		0	0	

- 4000
+ 5000
→ 1000

- 2000
+ 1000
→ - 1000

Patients with vmPFC impairment



RAW CHOSES SCORES

A B: Disadvantageous
C D: Advantageous
E G: Advantageous
F H: Disadvantageous

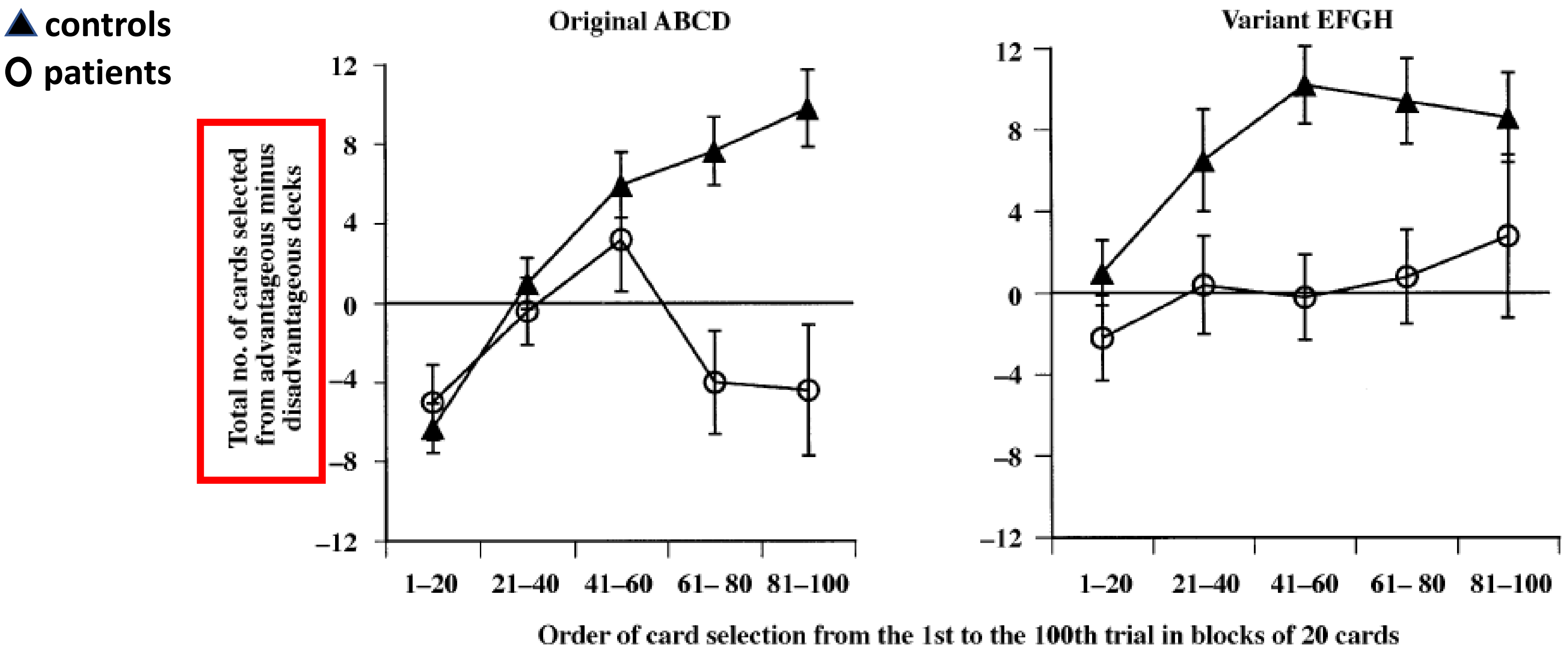
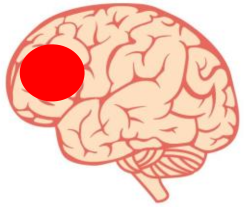


Fig. 2 Decision-making in the original (ABCD) and variant (EFGH) versions of the gambling task. Relative to normal controls (filled triangles), VM lesion patients (open circles) were impaired in their performance on both the original (ABCD) and variant (EFGH) versions of the gambling task. The figure shows net scores [(C + D) – (A+B) or (E + G) – (F + H)] of cards selected by each group across different blocks expressed as mean ± SEM. Positive net scores reflect advantageous performance whereas negative net scores reflect disadvantageous performance.

Patients with vmPFC impairment



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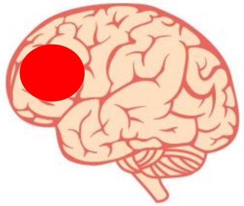


▲ controls
O patients

RAW CHOSES SCORES

Variant with:

1) **Decrease** in **delay** for future **rewards** (variant EFGH)
2) **Increase** in **delay** for future **punishments** (variant ABCD)

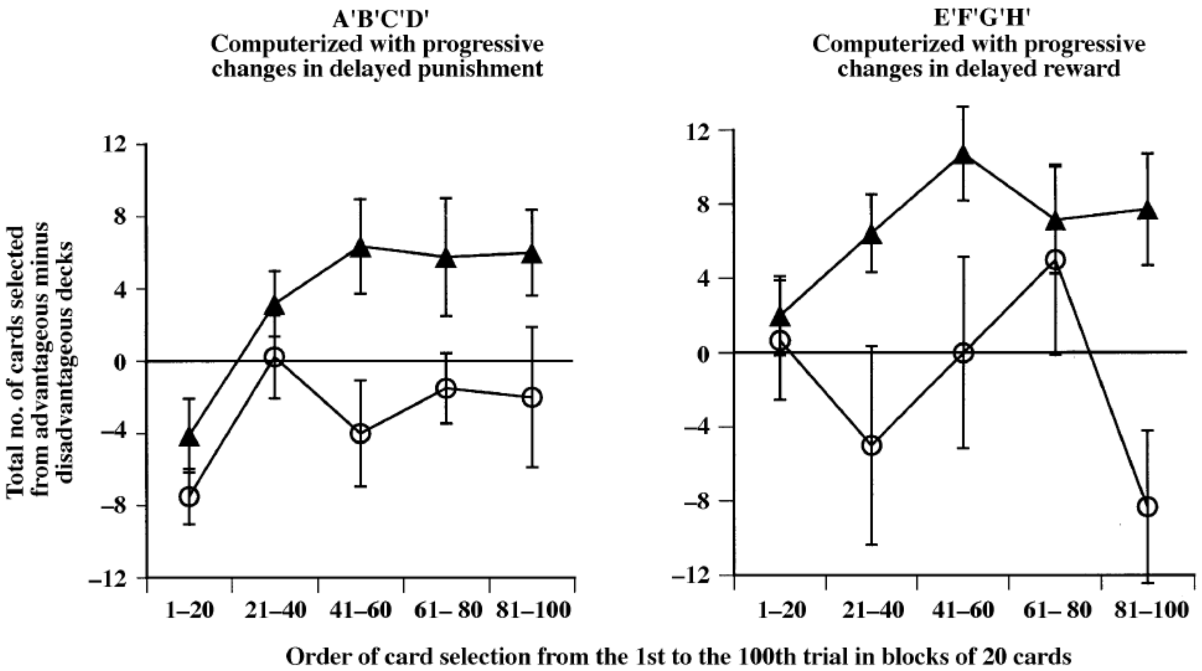
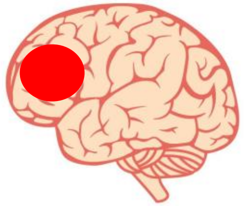


Fig. 4 Decision-making on computerized changes in delayed punishment (A′B′C′D′) and reward (E′F′G′H′). Despite introducing progressive increase in delayed punishment or progressive decrease in delayed reward, VM lesion patients failed to shift their behaviour away from these disadvantageous decks. Relative to normal controls (filled triangles), VM lesion patients (open circles) were impaired in their performance on the computer version of both the original (A′B′C′D′) and the variant (E′F′G′H′) gambling task. The figure shows net scores [(C′ + D′) – (A′ + B′) or (E′ + G′) – (F′ + H′)] of cards selected by each group across different blocks, expressed as mean ± SEM. Positive net scores reflect advantageous performance whereas negative net scores reflect disadvantageous performance.

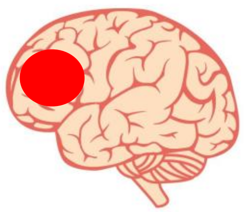
Patients with vmPFC impairment



Results suggest that patients with VM lesions are insensitive to future consequences, positive or negative, and are primarily guided by immediate prospects. This “myopia” for the future in VM lesion patients persist in the face of severe adverse consequences, i.e. rising future punishment or declining future reward.

Possibility 1: HYPERSENSIBILITY to REWARD	Possibility 2: INSENSITIVITY to PUNISHMENT	Possibility 3: INSENSIBILITY to FUTURE consequences (positive or negative)
• The prospect of a large immediate gain outweighs any prospect of future loss	• The prospect of a large loss cannot override any prospect of gain	• Patients are oblivious to the future and completely guided by the present

Patients with vmPFC impairment



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Damage to ventromedial prefrontal cortex impairs judgment of harmful intent

Liane Young[1,*], **Antoine Bechara**[2], **Daniel Tranel**[3], **Hanna Damasio**[2], **Marc Hauser**[4], and **Antonio Damasio**[2]

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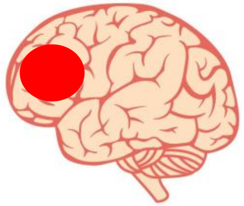
[4] Departments of Psychology and Human Evolutionary Biology, Harvard University, Cambridge, Massachusetts 02138, USA

Patients with vmPFC impairment



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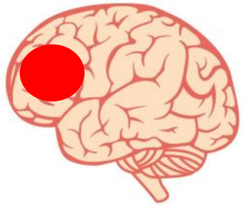
Damage to ventromedial prefrontal cortex impairs judgment of harmful intent

Experimental questions:

1. The aim of the current study is to understand the causal role of the **ventromedial prefrontal cortex (VMPC)** for such moral judgments that rely on assessments of intent in VM patients.

Patients with vmPFC impairment

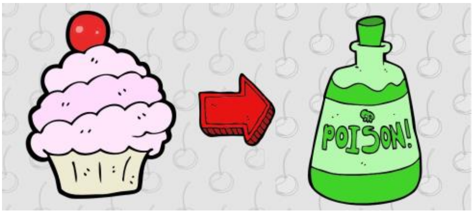


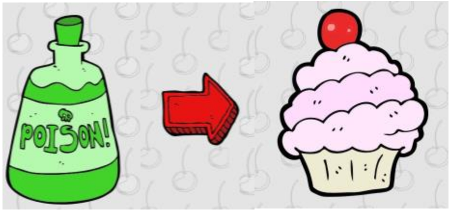
When we attempt to understand and evaluate other people's actions, we often draw inferences about their beliefs and intentions:

Did they **believe** they would cause harm?

Did they **intend** to cause harm?

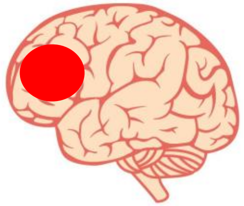
Typically, these **beliefs** and **intentions** **match** the action's **outcomes** but sometimes mismatches occur.





Prior neuroimaging and neuropsychological evidence has suggested a **role for the VMPC** in evaluating **harmful actions**.

Patients with vmPFC impairment



N=9 **patients** (with adult-onset, focal bilateral VMPC lesions) vs N=7 **controls** (with lesions that excluded VMPC, insula, amygdala and right SI and SII) vs. **normal** (no lesions).

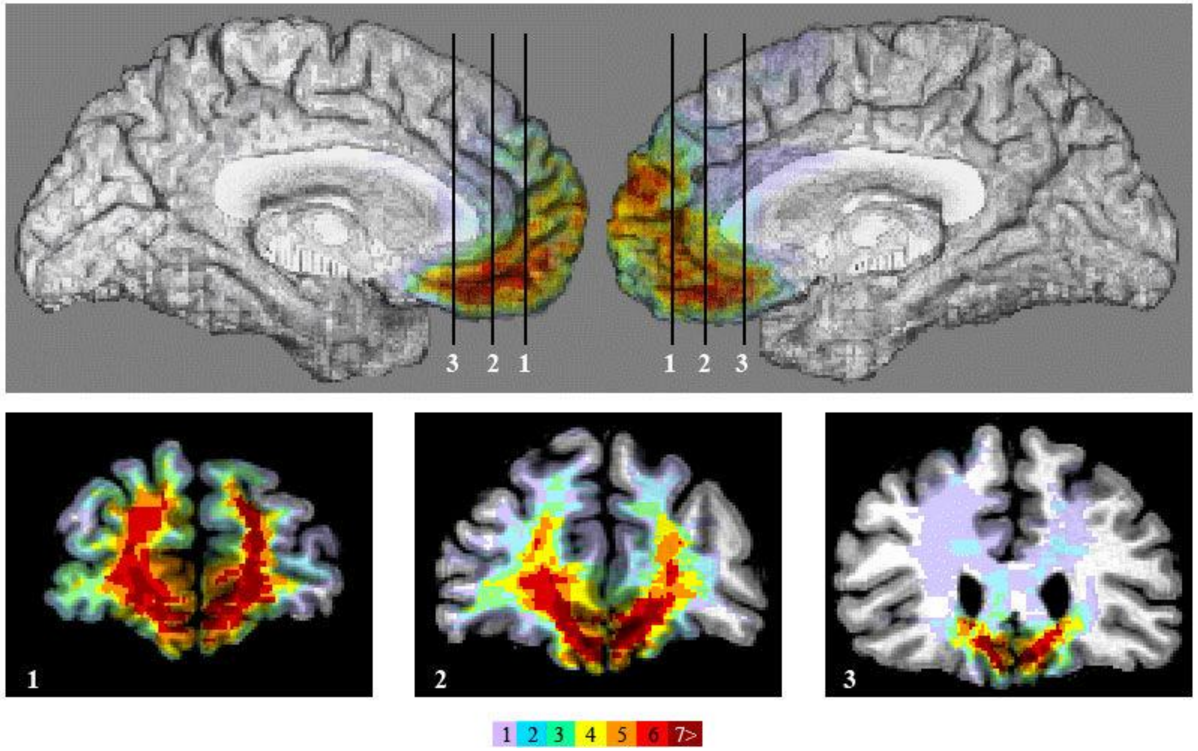
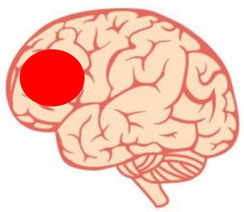


Figure 1.
Lesion overlap of the 9 VMPC subjects using the MAP-3 technique. Top panel shows the left and right mesial views of the template brain. Panels 1,2,3 show three coronal sections through VMPC at the levels indicated in the top panel. The numbers of overlaps at each voxel is shown in the color bar.

Patients with vmPFC impairment



24 scenarios (subjects saw 1 version of each scenario)

There were **four variations** (conditions) of each scenario, following a 2 × 2 design:

outcome

1) protagonists either **harmed** another person (negative outcome) or did **no harm** (neutral outcome);

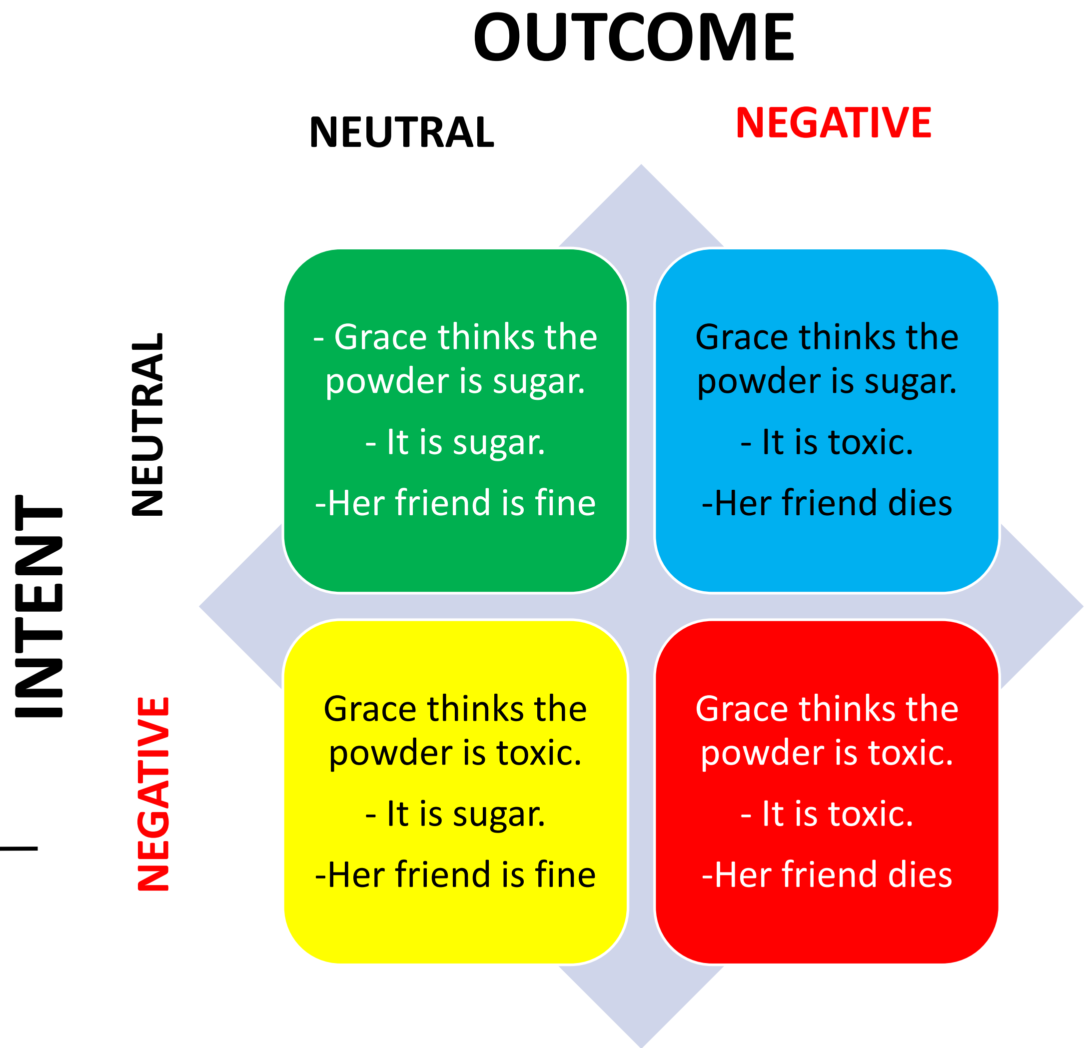
intent

(2) protagonists either **believed** they would cause harm (negative intent) or **believed** they would cause **no harm** (neutral intent).

OUTCOME

INTENT	**NEUTRAL**	**NEGATIVE**
NEUTRAL	- Grace thinks the powder is sugar. - It is sugar. -Her friend is fine	Grace thinks the powder is sugar. - It is toxic. -Her friend dies
NEGATIVE	Grace thinks the powder is toxic. - It is sugar. -Her friend is fine	Grace thinks the powder is toxic. - It is toxic. -Her friend dies

If you have to judge…



Patients with vmPFC impairment

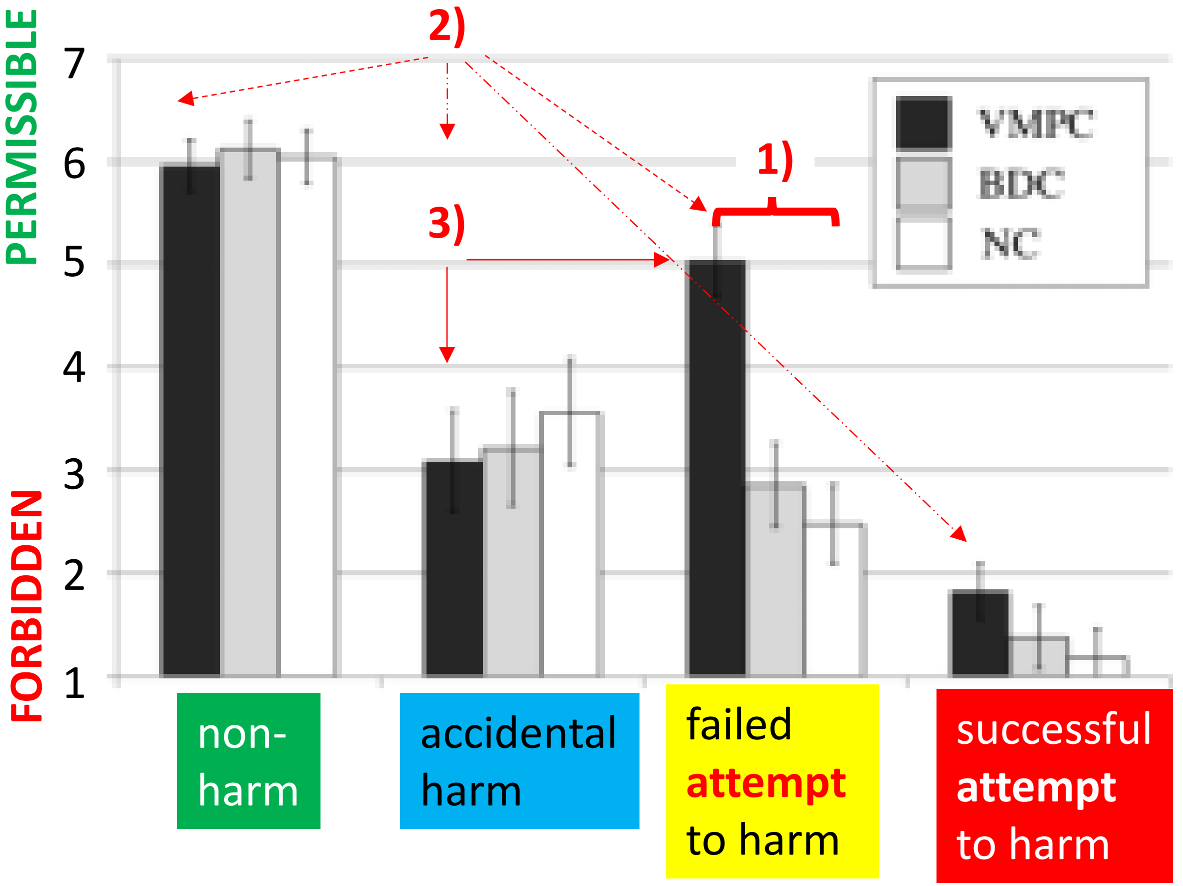
RESULTS:

1) VMPC participants judged **failed attempted harms** as more permissible than BDC participants (p=0.001) and NC participants (p<0.001).

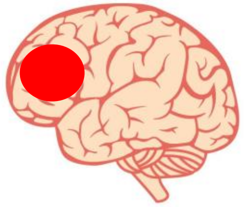
2) VMPC participants' judgments did reflect a difference between **failed attempted harms** and **non harms** (p=0.018), and a difference between **accidental harms** and **successful attempts to harm** (p<0.001). Thus, VMPC participants were able to distinguish between these conditions by representing the content of negative beliefs and intentions

3) VMPC participants also judged **failed attempted harms** as significantly more permissible than **accidental harms** (t(8)=3.7, p=0.006), a pattern that was significantly different from the pattern observed in the BDC participant group (p=0.037) and the NC participant group (p=0.003) (see next slide).

Moral judgments for all four conditions. Judgments are shown for each participant group, on 7-point scale



Patients with vmPFC impairment

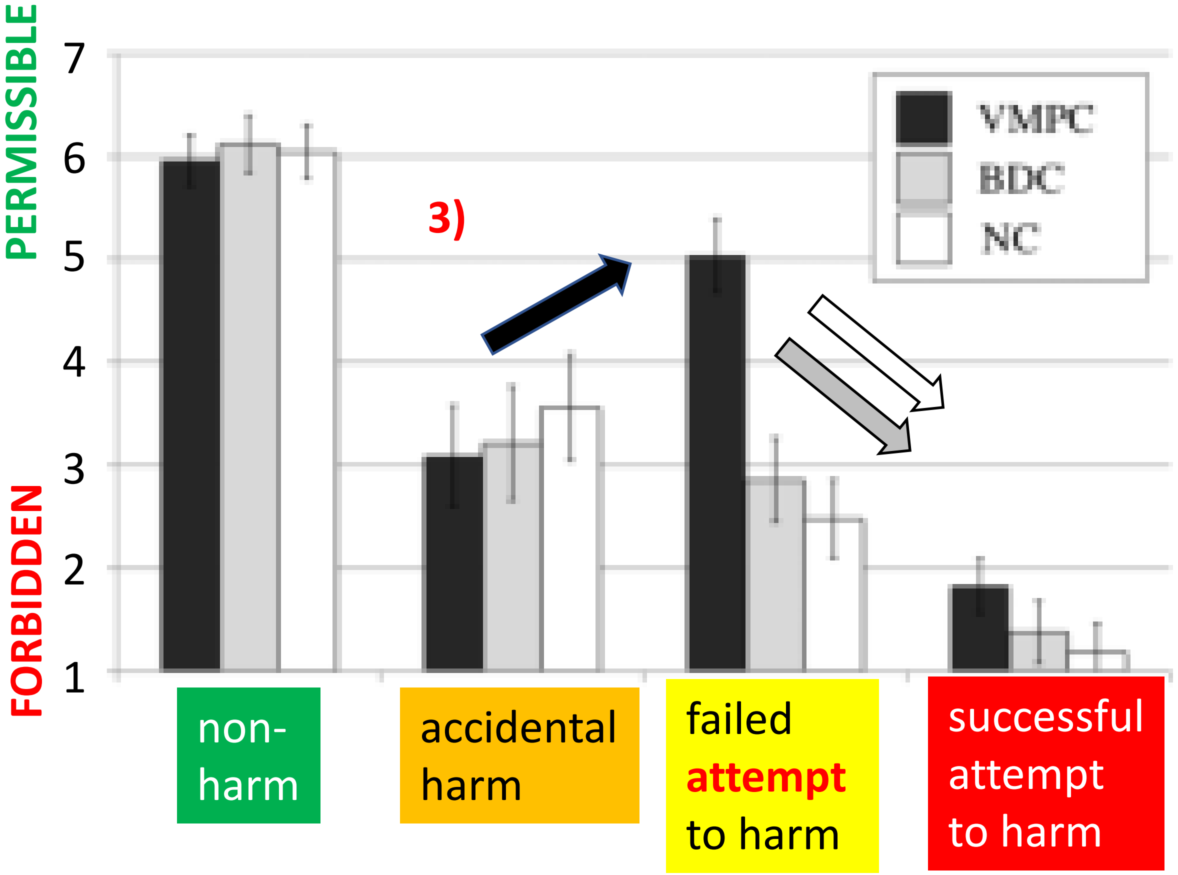


CONCLUSIONS: of moral judgements (only results, not the whole experiment)

VMPC participants judged attempted harms as more morally permissible than both contorl groups.

VMPC participants even judged attempted harms (e.g., attempting, but failing to poison someone) as more permissible than **accidental harms** (e.g., accidentally poisoning someone).

Notably, the pattern of moral judgments delivered by the VMPC patients represents not just a departure from but also **a reversal of the normal pattern** of moral judgments. Among healthy adults and even young children, **attempted harms are generally judged quite harshly (forbidden)** and usually more harshly than accidental harms (Cushman, 2008; Piaget, 1965/1932).



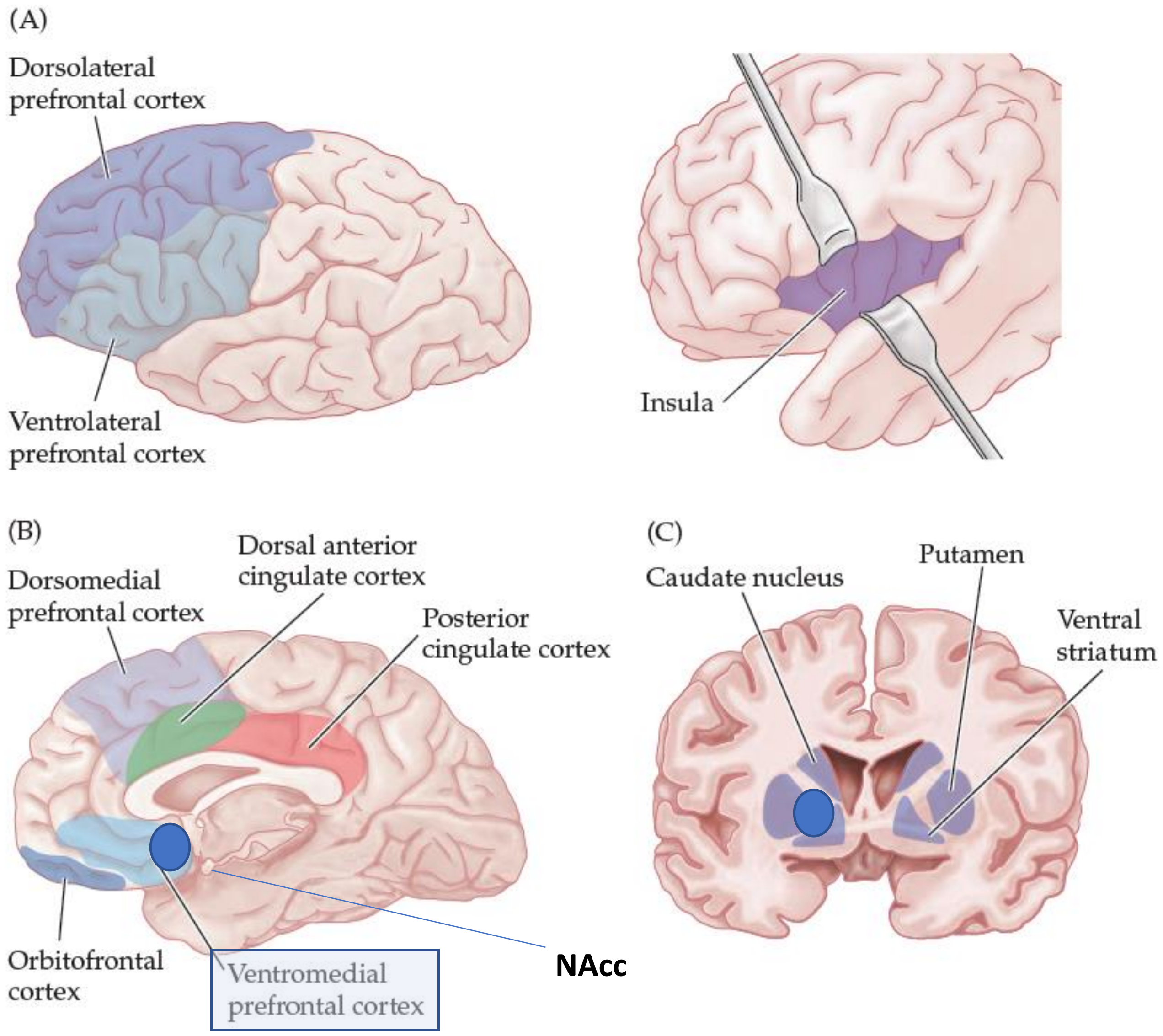
Summary

- A Sketch of the Relevant Circuitry
- Nucleus Accumbens (Nacc)
- Orbitofrontal Cortex and Ventromedial Cortex: Evaluation of Options
- **Dorsolateral Prefrontal Cortex and the Planning and Organization of Behavior**
- Cingulate Cortex and Learning from the Consequences of Behavior
- Ventrolateral Prefrontal Cortex and Self-Control

Role of DLPFC

DLPFC →consists primarily of Brodmann's areas 9
and 46 and is connected to several other cortical regions (ACC, OFC, premotor cortex…)

<u>Role</u>: Planning and Organization of Behavior **flexibly**



Role of DLPFC

Accordingly, the function of the DLPFC is sometimes likened to switching in a railroad yard, rerouting connections between different tracks to align trains from their origins with their intended destinations

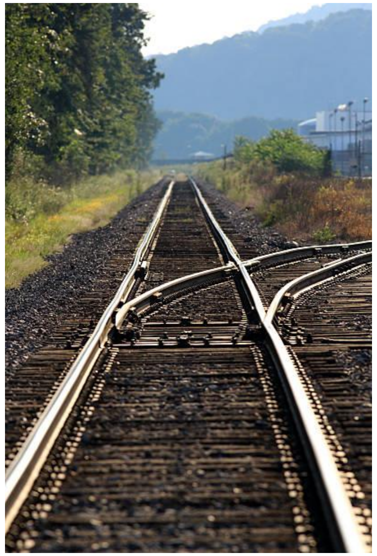
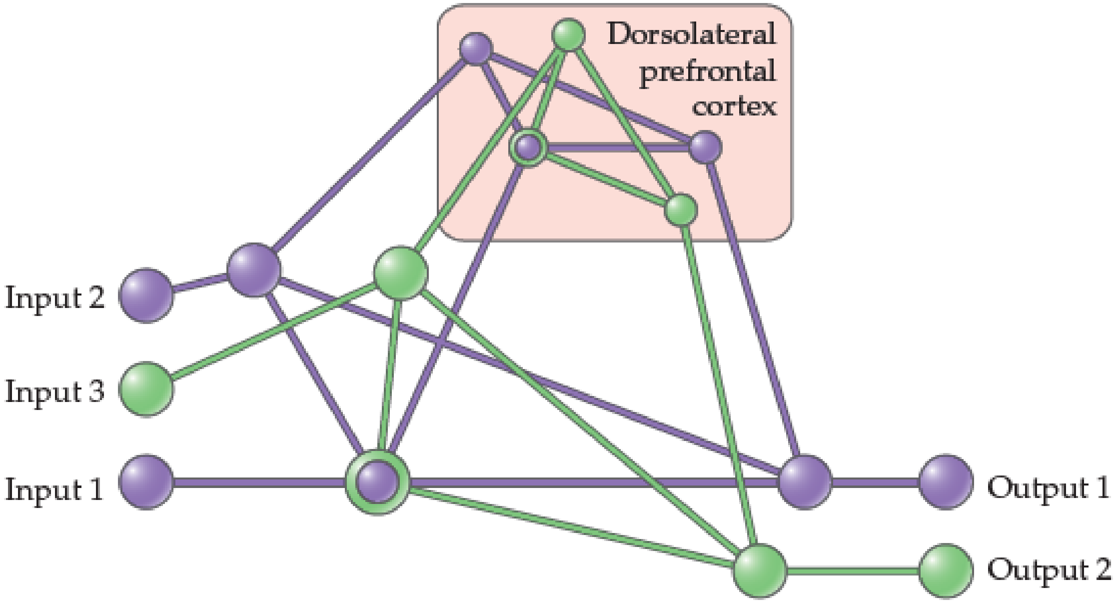
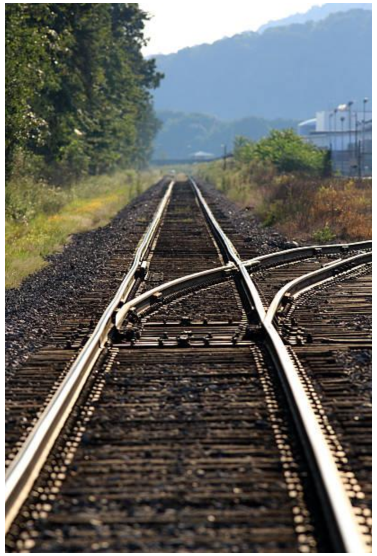


FIGURE 32.6 Schematic illustration of the function of the dorsolateral prefrontal cortex. The brain can be thought of as a network that transforms inputs to outputs through information propagated along weighted connections. The path that information takes is, in turn, influenced by regulatory units thought to be housed in the DLPFC. These regulatory units receive information from other units in the system. (After Miller, 2000.)



Role of DLPFC



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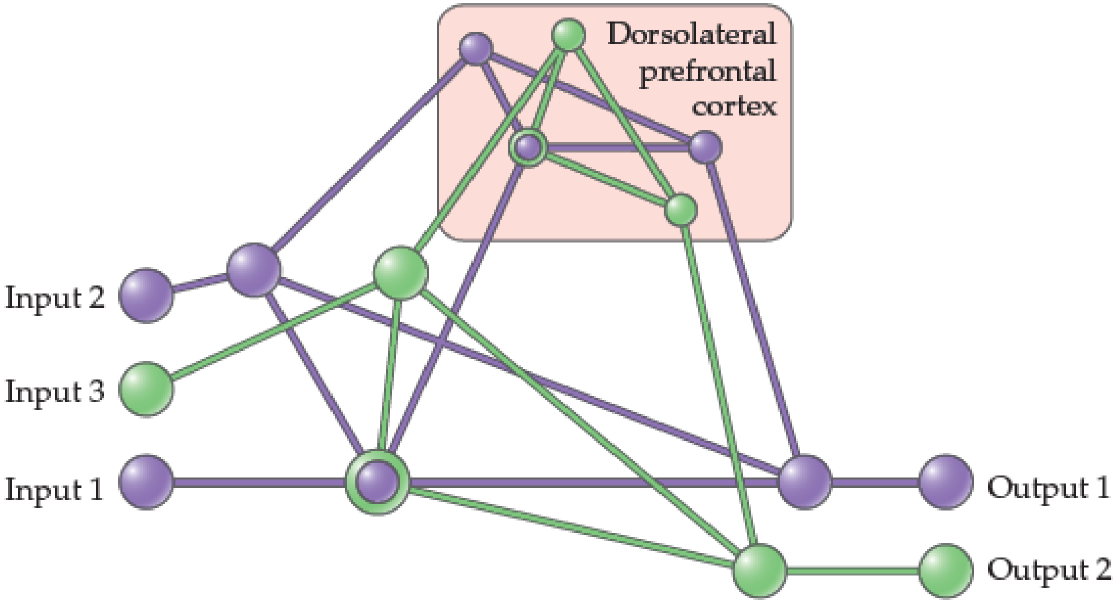


Role of DLPFC

- the DLPFC may control the responses of other groups of neurons, making them more or less responsive to inputs and feedback, thereby producing different responses in different contexts
- DLPFC → role in short-term memory the ability to keep information in mind to guide behavior
- Storage of information in short-term memory reflects changes in the firing rates of neurons in various regions of the brain, including the DLPFC. Specifically, **firing rates** of neurons in the DLPFC **increase** while **information** is maintained in **short-term memory**
- Damage to the DLPFC is associated with impairments in short-term memory capacity and duration

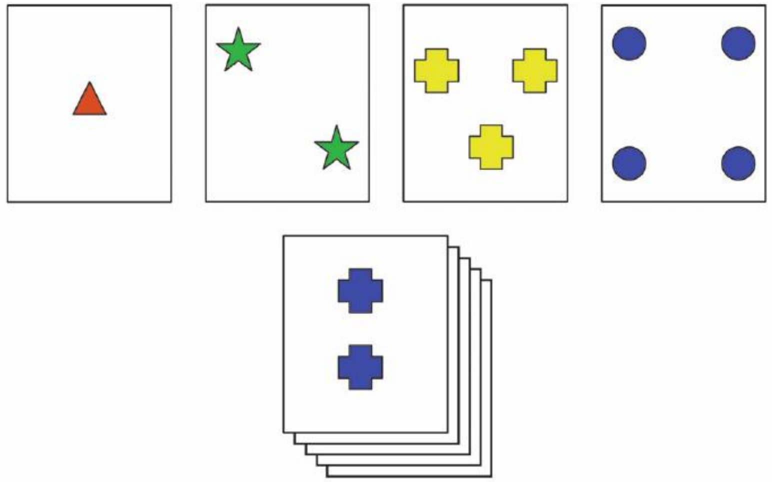
Role of DLPFC

- Another key element in cognitive control is maintenance of rules and corresponding changes in behavior when the rule change.

- Neurons in DLPFC show systematic patterns of activity that accord with specific rules, suggesting this area also maintains a representation of abstract information that guides complex behaviours

- Moreover, systematic changes in the firing rates of neurons in the DLPFC accompany changes in the rules that govern effective behavior in a particular context.

Role of DLPFC



- Es. WCST Wisconsin Card Sorting Task
- An individual is shown a set of cards, each of which has a different number of distinct shapes of varying color. The individual must then place a new card according to an unstated rule, such as shape, color, or number. After a series of trials, the rule is surreptitiously switched.
- Patients with DLPFC damage can learn to perform this task using the initial rule, but when the rule is changed they tend to **continue with the old one** and perform poorly. This impairment corresponds to the tendency for patients with DLPFC lesions to become stuck in behavioral routines and not adapt to changing circumstances.

DLPFC disruption

Diminishing Reciprocal Fairness by Disrupting the Right Prefrontal Cortex
Daria Knoch, *et al.*
Science **314**, 829 (2006);
DOI: 10.1126/science.11291

- The disruption of the **right**, but not the left, DLPFC by low-frequency rTMS substantially **reduces subjects 'willingness to reject** their partners 'intentionally unfair offers.

- Subjects are less able to resist the economic temptation to accept these offers.

- Importantly, however, subjects still judge such offers as very unfair, which indicates that the DLPFC plays a key role in the implementation of fairness-related behaviors.

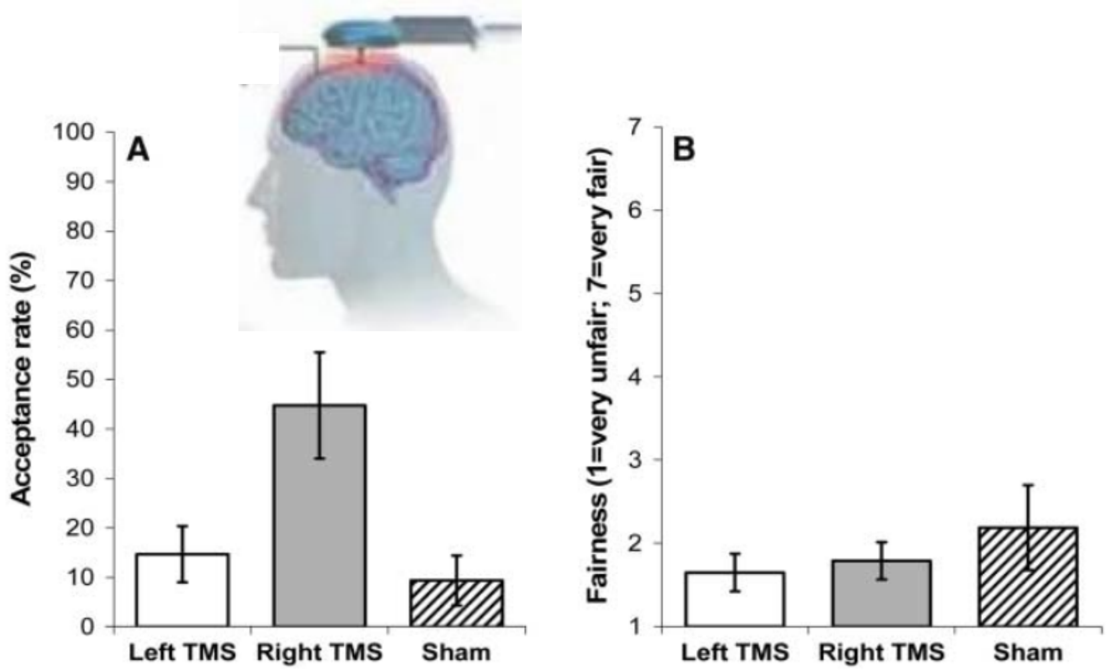


Fig. 1. Behavioral responses and fairness judgments (means ± SEM) related to the most unfair offer of CHF 4 in the human offer condition. (**A**) Acceptance rates across treatment groups. Subjects whose right DLPFC is disrupted exhibit a much higher acceptance rate than those in the other two treatment groups (Mann-Whitney U tests, two-tailed, $P < 0.05$). (**B**) Perceived unfairness across treatments (1 = very unfair; 7 = very fair). Subjects in all three treatment groups perceive an offer of 4 as very unfair, and there are no significant differences across groups.

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ACC (Area 24, parts of areas 9, 6, 32)

- Humans and other “intelligent” animals are capable of **learning from the consequences of their actions**. Doing so requires circuitry that can evaluate the outcomes of decisions and update the control systems that regulate the connections between stimulus inputs and behavioral outputs
- Such monitoring is most strongly associated with the anterior cingulate cortex (**ACC**). This region is well positioned to serve this role since it has multiple inputs conveying information from a variety of systems, including perception, emotion, attention, and memory.

ACC as source of ERN (error related negativity)

- ACC is thought to be the source of the error-related negativity (ERN) in EEG studies
- The ERN signal is observed in standard laboratory tasks immediately after (or in some cases just before) an individual commits an error.
- Due to the poor localization of EEG signal sources, it is difficult to know with much precision which part of the brain actually generates the ERN. However, circumstantial evidence supports the idea that it arises from the ACC.

ACC

- Activity in the ACC is also consistent with the evaluation of outcomes and generation of feedback signals useful in updating behavioral goals and the adoption of new cognitive rules.
- Responses of ACC neurons are affected not so much by the nature of options or their values, but by the **consequences of choosing them**.
- In laboratory studies, ACC activated by errors that reduce rewards, which in real life would correspond to disappointment in not achieving a goal
- The ACC also tracks counterfactual or fictive outcomes—in other words, the rewards or punishments associated with options that were not chosen.

ACC and Stroop effect

- ACC is involved in dealing with such conflicts
- Direct electrophysiological recordings from the ACC in human neurosurgical patients show evidence of this conflict
- Damage to the ACC leads to impairments in learning from the consequences of actions.
- An example is obsessive-compulsive disorder (OCD), which is associated with atypical levels of activity in the ACC.

In a typical Stroop scenario, people are faster saying the word red when it is printed in red ink than they are when it is printed in green ink

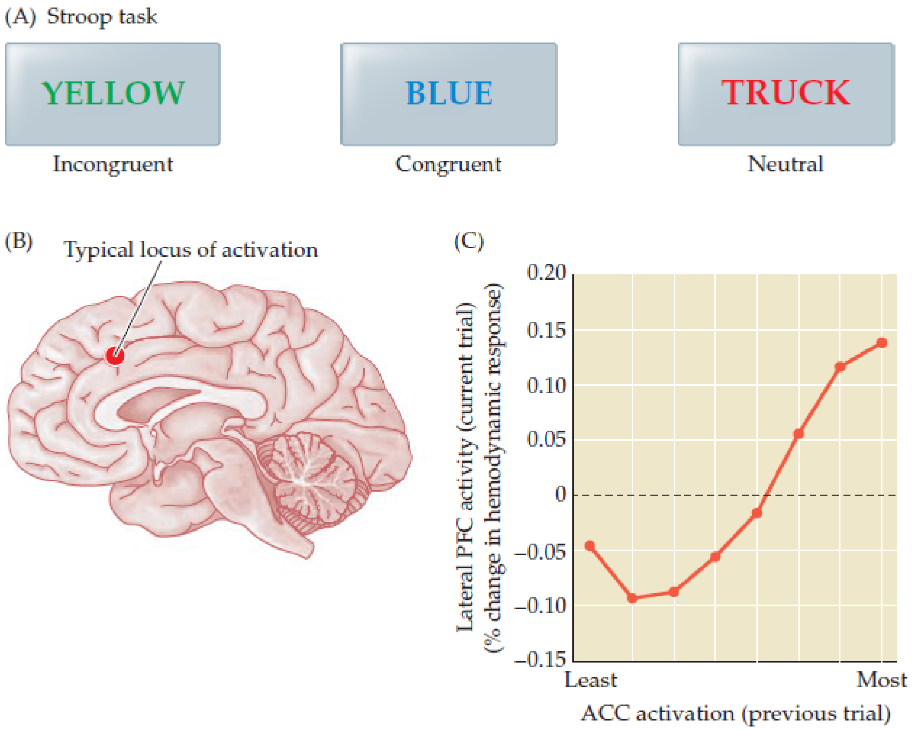

FIGURE 32.9 Anterior cingulate cortex and the Stroop effect. (A) In the Stroop task, individuals are asked to say a word printed in a color on a card or computer screen. When the word is incongruent—a different color than the color of the ink—individuals are slower to respond. When the word is neutral (not color related) or congruent (same color), individuals have no difficulty responding. It is thought that the competition between saying the word and saying the ink color come into conflict. (B) During cognitive conflict, responses in the anterior cingulate cortex (ACC) are greatly enhanced. (C) Following conflicting trials, individuals adjust their behavior to improve performance. This adjustment is thought to reflect changes driven by inputs to the dorsolateral prefrontal cortex from the ACC. Activation of the ACC on the previous trial, as measured by fMRI-predicted the response in the DLPFC on the current trial, predicts adjustment. (B after Bush et al., 1998; C after Kerns et al. 2004.)

ERN and ACC

- 2 players (A and B) and 2 pennies
- Each player has to secretly turn the penny to heads or tails

IF the pennies match (both heads or both tails) → PLAYER A KEEPS BOTH

IF the pennies do not match (one head and one tail) → PLAYER B KEEPS BOTH

What happens to our brain during this game?

Matching Pennies

	Head	*Tail*
Head	1,-1	-1,1
Tail	-1,1	1,-1

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Behavioral/Systems/Cognitive

Reinforcement Learning Signals Predict Future Decisions

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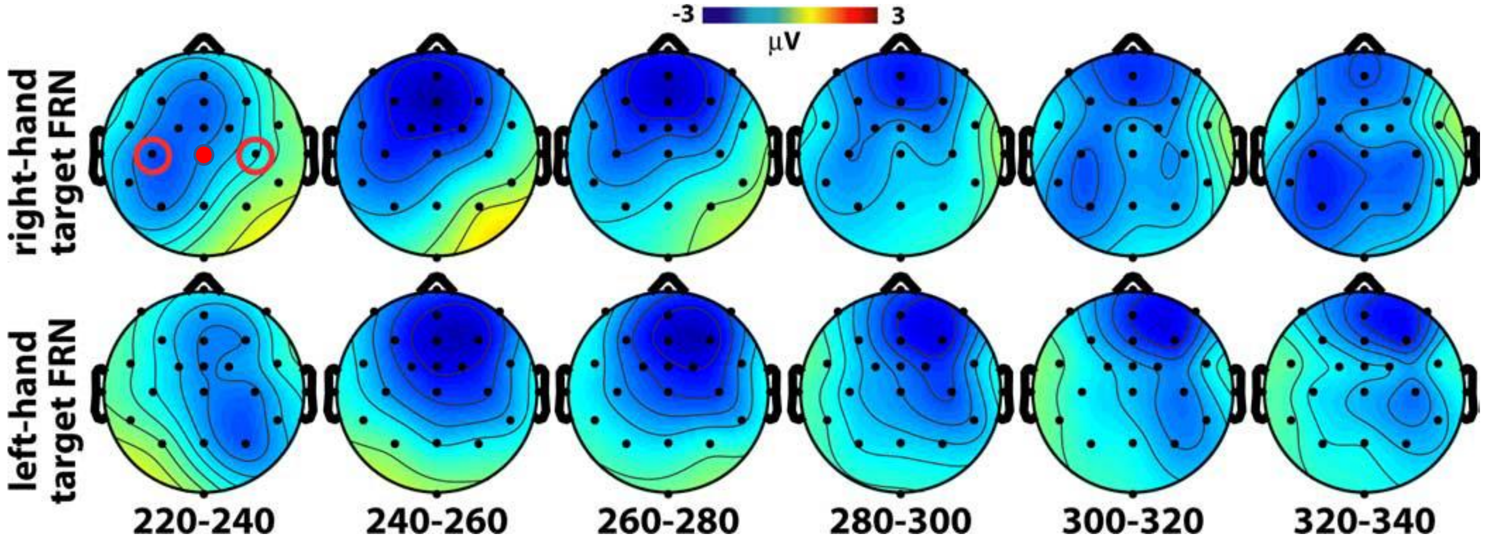
Authors recorded **event-related brain potentials** (ERPs) while subjects played a pennies game against a computer opponent to evaluate **how neural responses to outcomes related to subsequent decision-making**.



They measure an outcome-locked potential thought to reflect **a neural prediction error signal**.

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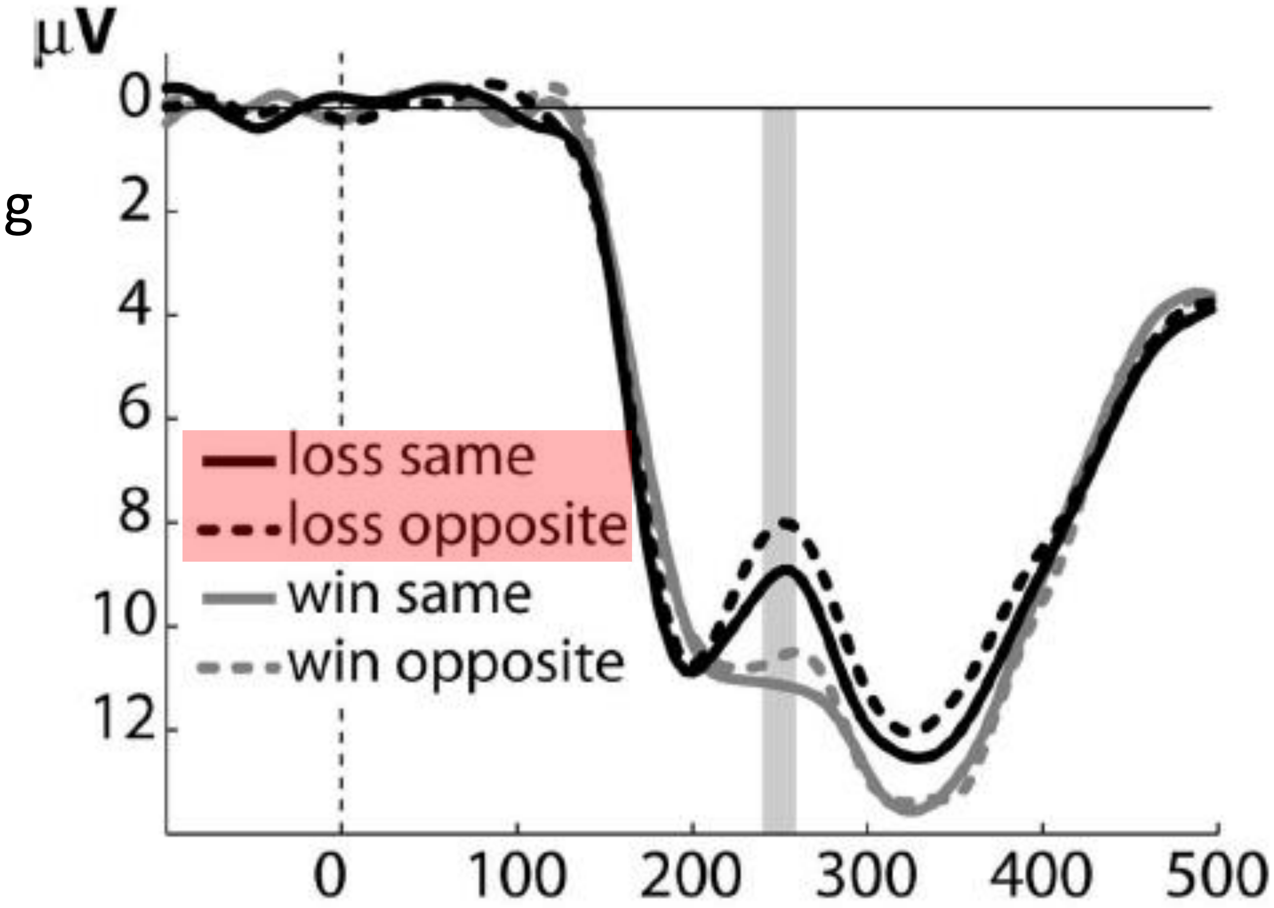
The graph shows evoked responses to losses and wins.

loss/same → the subject lost and chose the same target on the following trial as on the current one

loss/opposite →the
subject lost and chose the opposite target on the following trial as on the current one



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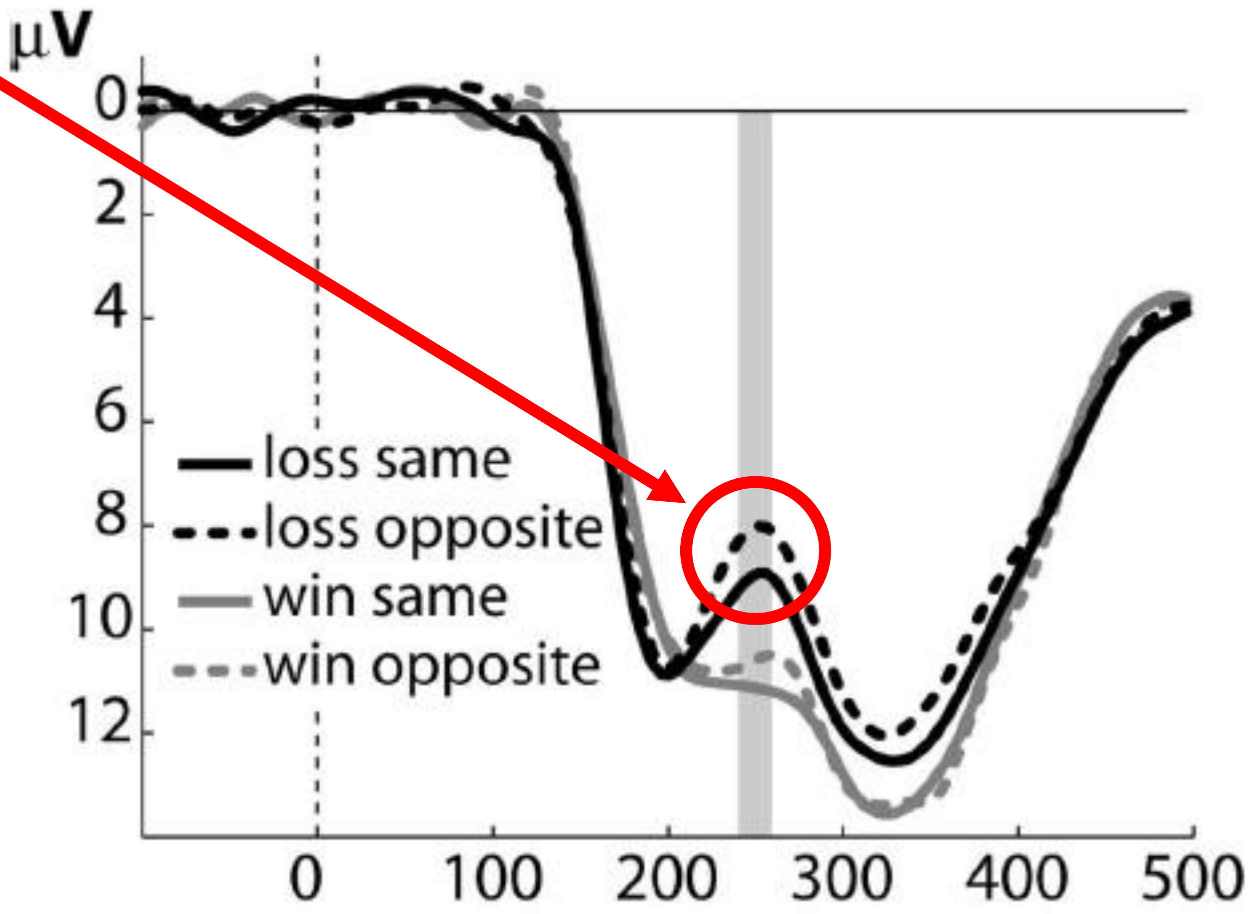
When the person loses money, there is a peak around 250 milliseconds

This peak is particularly higher when person **changes** decision in the next round (▬▬) compared to the loss same situation (- - -).

The **magnitude** of ERPs after losing to the computer opponent **predicted** whether subjects would change **decision** behavior on the subsequent trial.



Feedback-related-negativity waves to decision outcomes were disproportionately larger over the motor cortex contralateral to the response hand that was used to make the decision.

Behavioral/Systems/Cognitive

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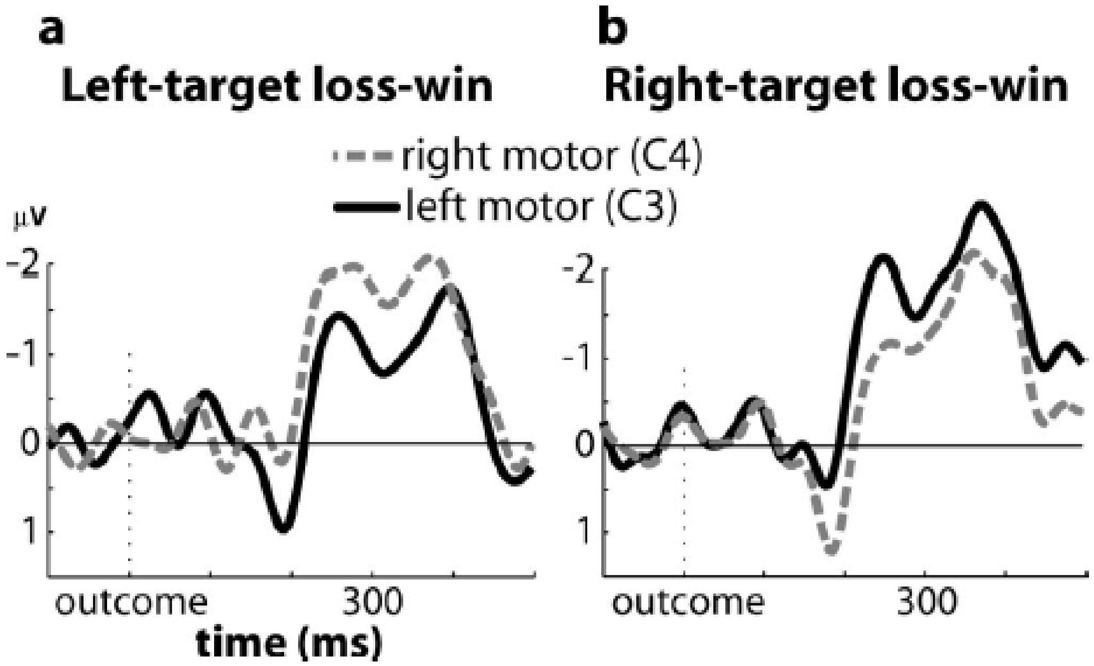


Figure 5. ERP evidence that feedback processing involves adjustments of representations of competing responses. Grand-averaged LFRN effects according to whether subjects chose the left-hand target (*a*) or the right-hand target (*b*). ERPs are shown from motor cortex electrode sites (C3 and C4). The LFRN difference is larger over right motor cortex after left target selections and is larger over left motor cortex after right target selections.

Summary

- A Sketch of the Relevant Circuitry
- Nucleus Accumbens (Nacc)
- Orbitofrontal Cortex and Ventromedial Cortex: Evaluation of Options
- Dorsolateral Prefrontal Cortex and the Planning and Organization of Behavior
- Cingulate Cortex and Learning from the Consequences of Behavior
- **Ventrolateral Prefrontal Cortex and Self-Control**

Ventrolateral Prefrontal Cortex (Area 44, 45, 12, 47)

- After deciding to act and preparing to do so, individuals sometimes **change their minds** and countermand their planned actions.
- Patients with damage to the ventrolateral prefrontal cortex (VLPFC) are impaired in this override function and **respond impulsively**
- They respond **more quickly but less accurately** in timed tasks, and in life make poor decisions in various domains, including purchases, dietary choices, and social interactions
- They say the first thought that pops into their mind, even if it is inappropriate; and they continue to make bad choices even when they recognize that these actions are harmful

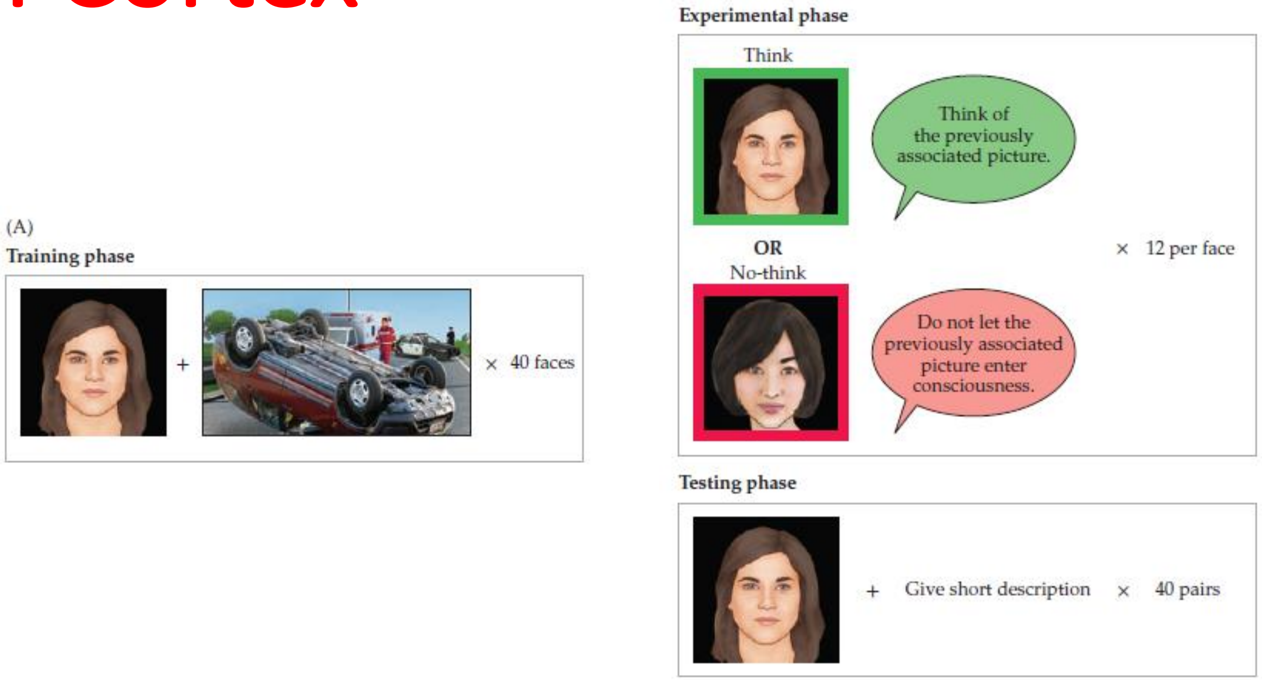
Ventrolateral Prefrontal Cortex

- The role of the VLPFC in inhibition is well documented
- When neuronal activity in VLPFC is enhanced (by TMS) an individual's ability to **suppress unwanted actions in laboratory tasks is improved**
- Identifying the mechanisms that mediate behavioral inhibition involves using tests that target the ability to countermand learned or habitual actions. The go/no-go task is an example.

Ventrolateral Prefrontal Cortex

- Individuals are told to perform a specific action when they see a stimulus—for example, press a button when a green light is illuminated.
- But occasionally a subsequent stimulus—say a red light—appears and supplants the first one, and the individual must ignore the green light and withhold the initially planned action
- Such tasks reliably and selectively activate the VLPFC, and damage to the VLPFC impairs performance on this task.

Ventrolateral Prefrontal Cortex



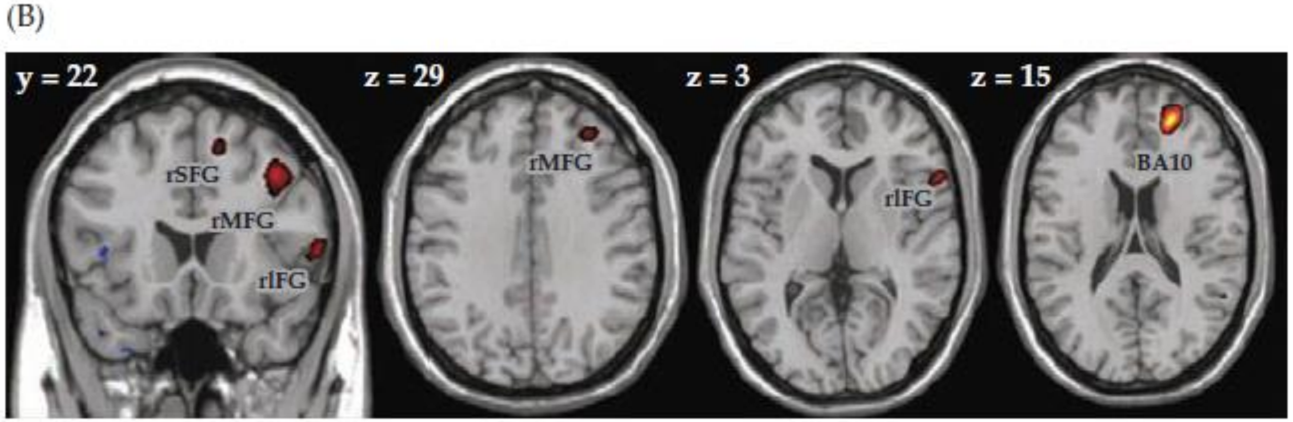


FIGURE 32.10 Role of the ventrolateral prefrontal cortex in behavioral inhibition. (A) In one experiment, individuals learned to associate faces with particular scenes. Following training, presentation of the face naturally led to recall of the associated scene. On some trials, individuals were asked not to think of the associated scene—that is, to inhibit the thought process. (B) Deliberate inhibition of thought led to activation of the right inferior frontal gyrus (rIFG), a major component of the VLPFC. Colored areas indicate regions of hemodynamic activation. Y/Z measures indicate sagittal and coronal positions of brain images. Other regions activated, and thus potentially involved in inhibition, include Brodmann's area 10 (BA 10), the right medial frontal gyrus (rMFG), the right superior frontal gyrus (rSFG), and the right lateral frontal gyrus (rLFG). (From Depue et al., 2007.)